Solar Energy Technologies: Research, Applications and Opportunities

Presentation to DOE/National Association of State Universities and Land Grant Colleges (NASULGC)

August 3, 2004

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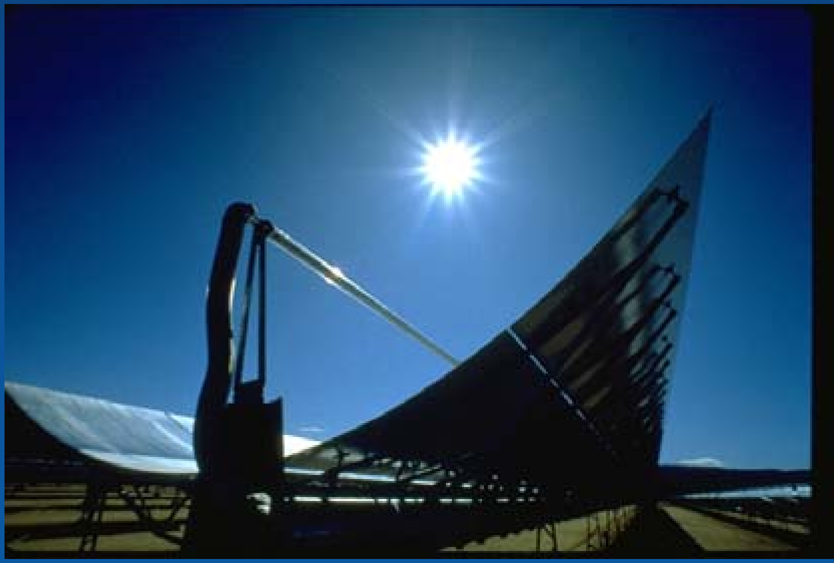
Electronic Materials and Devices

Solar Technology Programs

- Photovoltaics (PV)
- Concentrated Solar Power (CSP)



- Solar Thermal
- Solar Lighting

Solar Lighting

Each 3 mm fiber carries 350 lumens

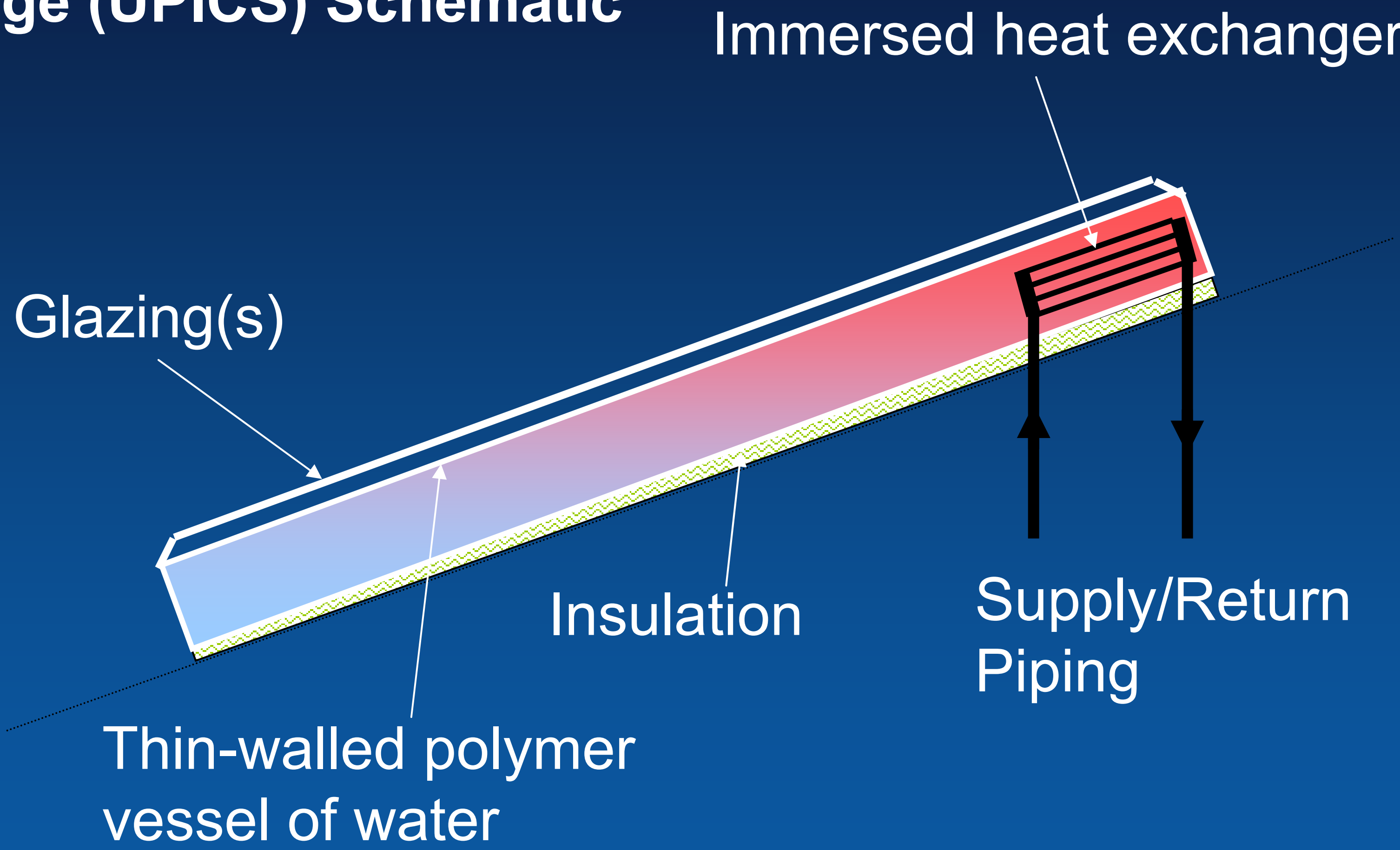
Estimated Itemized Cost in Small (~500 units) Quantities

- Primary/secondary mirror - $200.00
- Balance of roof-mounted system - $1,000.00
- Light Distribution - $1,200.00
- Hybrid Luminaires/Controls - $600.00
- Building Preparation - $500.00
- Installation/Alignment/Calibration - $500.00
- Total - ~$4,000.00 per m^2 of collection area

Estimated Levelized Cost 0.12 $/kWh

Low-Cost Solar Water Heaters

Unpressurized, Integral Collector Storage (UPICS) Schematic



Low-Cost Solar Water Heaters

Status:
Mild climates: $0.08 - $0.10/kWh in 2003
Cold climates: $0.12 - $0.14/kWh in 2003

Technical Challenges:

- **Polymer durability** – the **key** technical challenge
- **System performance**
  - Overheating protection
  - Heat exchanger sizing and placement
- **Building code issues**
  - Use of plastics, e.g., flammability
  - Structural concerns, e.g., roof weight, wind loading
- **Manufacturing process design**
  - Thermoforming and rotomolding tolerances and temperature limits

Concentrating Solar Power

Power Tower

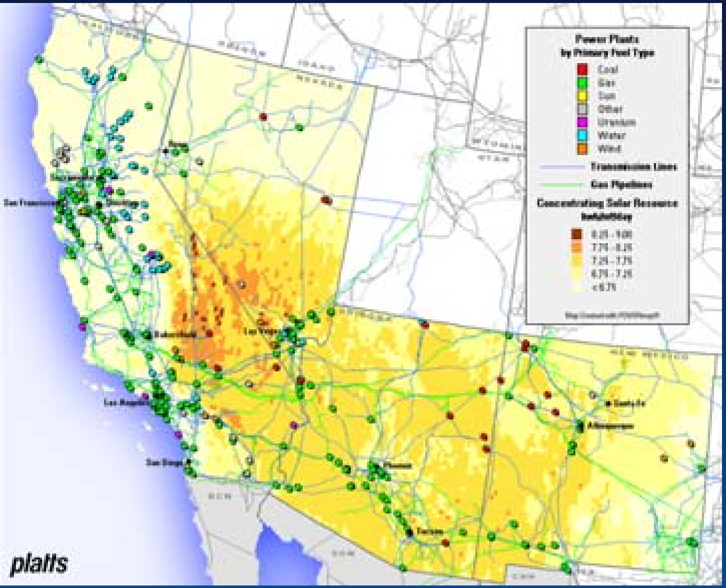
Concentrating Photovoltaics

Parabolic Trough

Dish/Stirling

SW Solar Energy Potential

State	Solar Capacity (MW)	Land Area (Sq Mi)
AZ	3,267,456	25,527
CA	821,888	6,421
NV	743,296	5,807
NM	3,025,920	23,640
Total	7,858,560	61,395



The table and map represent land that has no primary use today, exclude land with slope > 1%, and do not count sensitive lands.

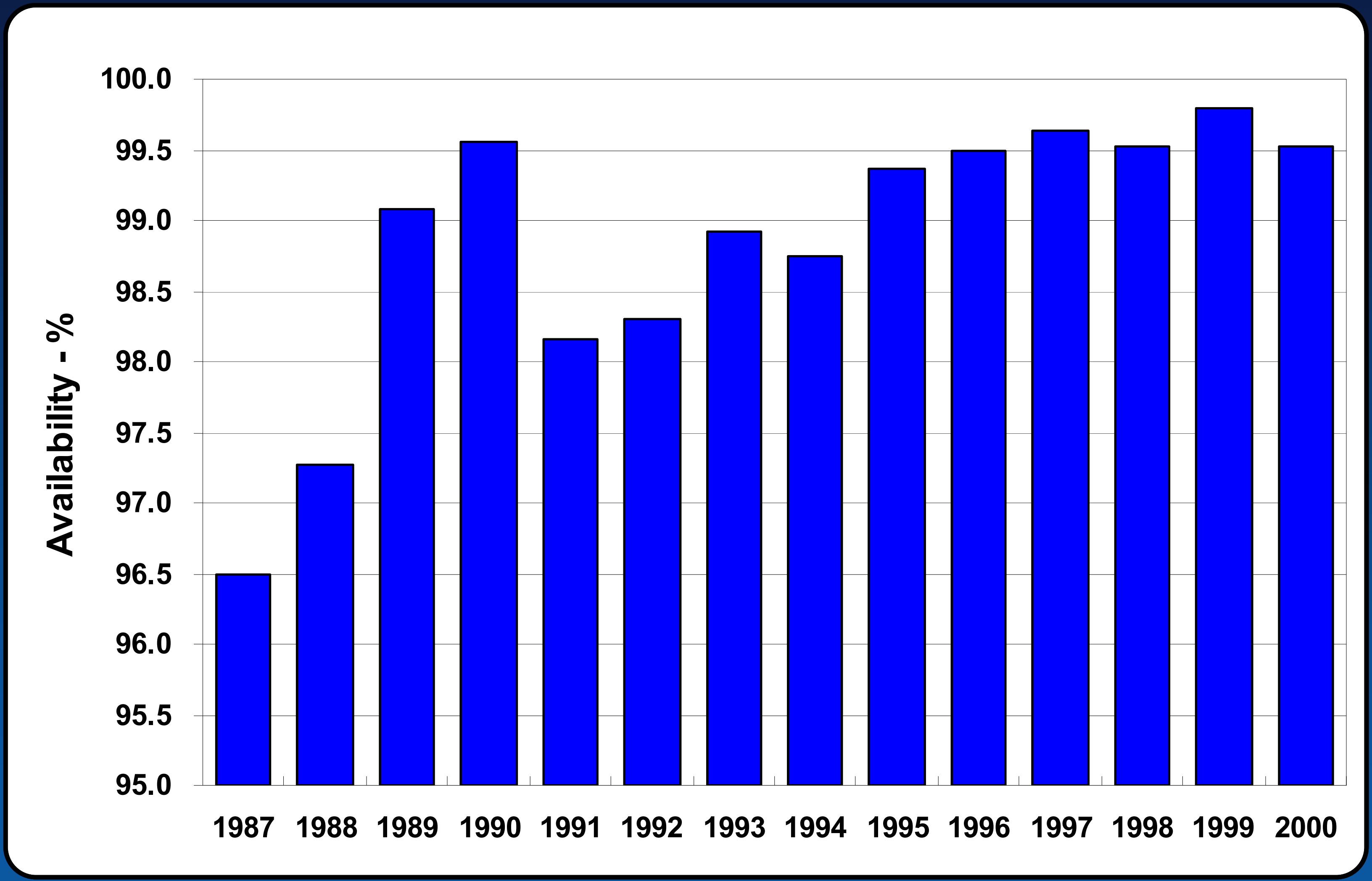
Solar Energy Resource ≥ 7.0 kWhr/m2/day (includes only excellent and premium resource)

Current total generation in the four states is over 100,000 MW.

Planned additions in four states over the next 3 – 5 years are 37,099 MW of which 87.6% is natural gas.

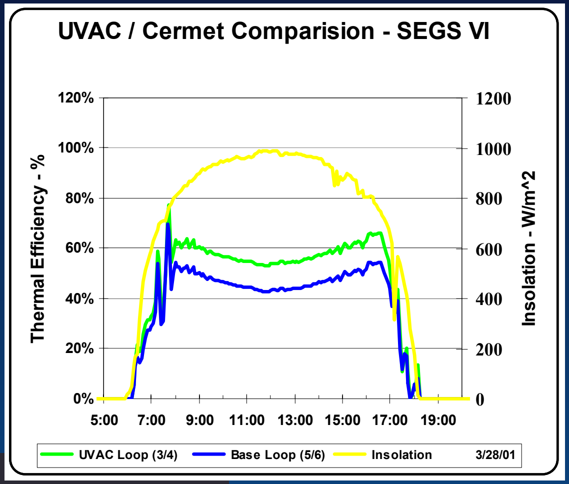
1000 MW of CSP requires 7.7 mi^2.

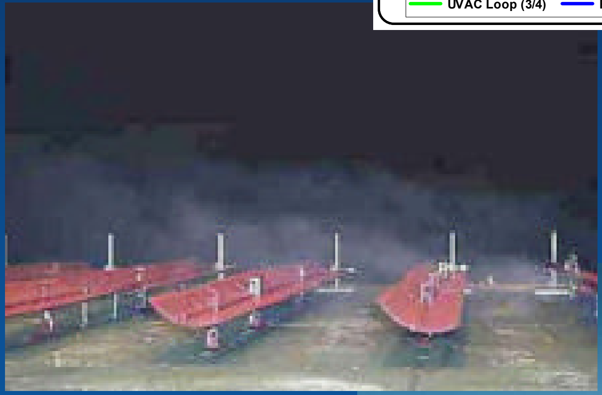
Kramer Junction SEGS Collector Availability



Concentrating Solar Parabolic Trough Systems

- **Current Advances**
  - 20% improvement in receiver efficiency
  - Development of lower-cost concentrator designs
  - ➢ Reduction in LEC from $.16/kWh to $.10/kWh





- **Projected Advances**
  - Integration w/ low-cost thermal storage
  - Improved efficiency through advanced receivers and high temperature operation
  - Cost reductions through plant scale-up
  - ➢ Reduction in LEC from $.10/kWh to $.04-$.06/kWh

Parabolic Trough Development Activities

- Trough R&D
  - Low-cost concentrator designs
  - Near- and long-term thermal storage
  - Advanced receiver designs
  - Alternative power cycles

1000 MW Initiative

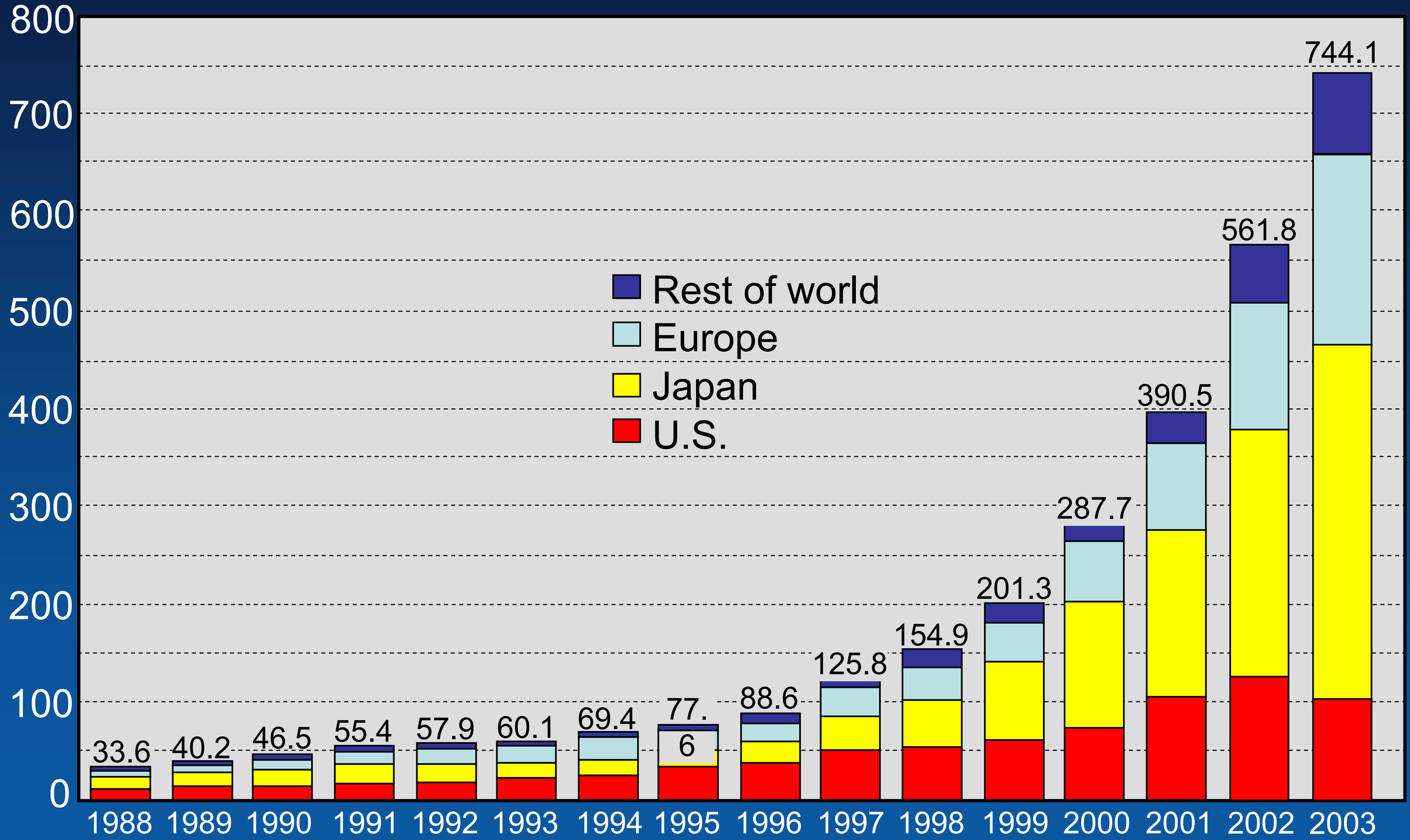
- In 2001 Congress asked DOE to determine what would be required to deploy 1000 MW of Concentrating Solar Power in the Southwest U. S.

- DOE and CSP industry approached the Western Governors' Association through the Western Interstate Energy Board to explore implementation.

- A number of Southwestern States have high solar potential and some have renewable energy portfolio standards (particularly, AZ, CA, NM, and NV) and the potential to gain from development of their solar energy resources.

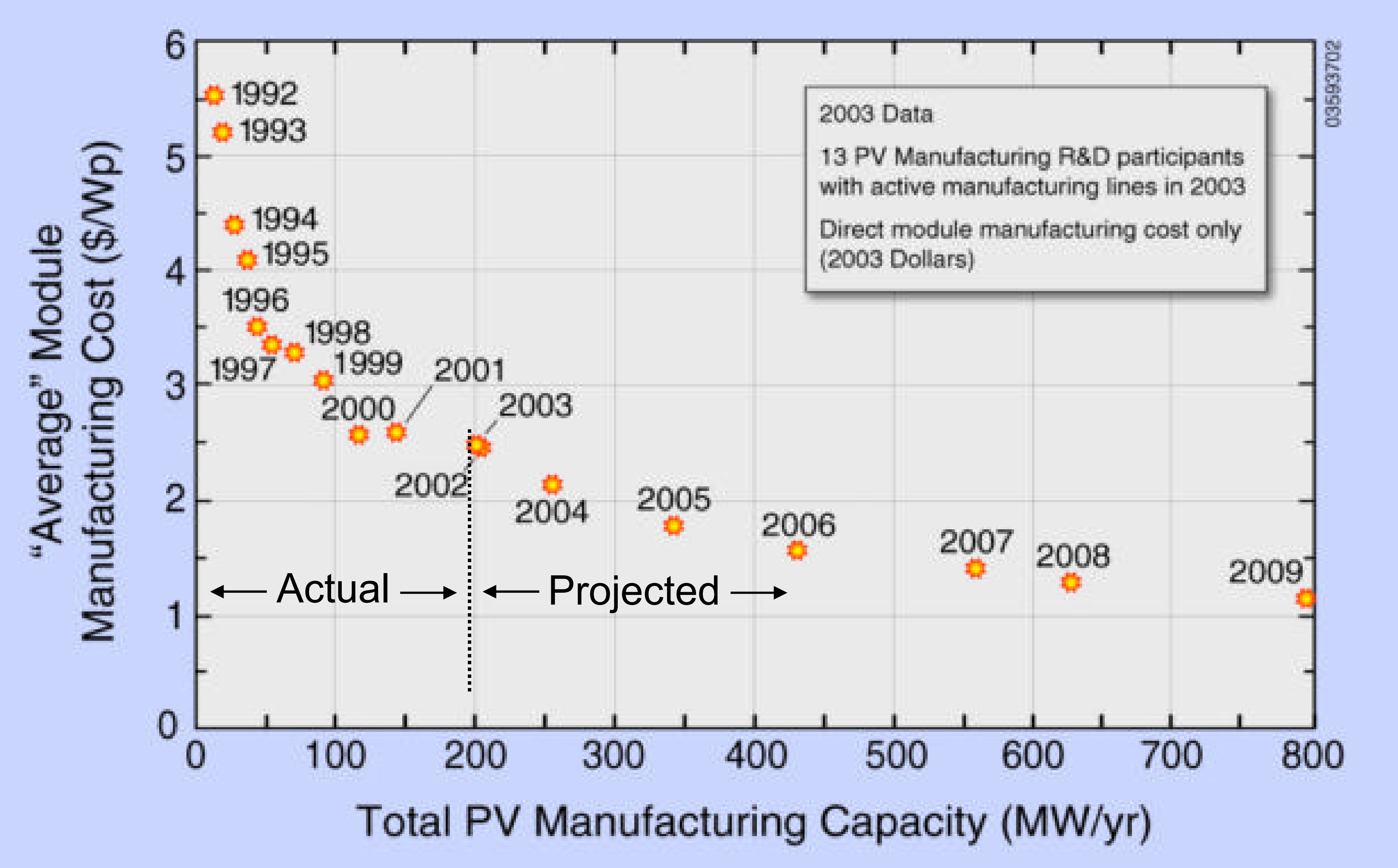
- Western Governors' likely to create Southwest Solar Task Force to investigate mechanisms for implementing regional initiative

World PV Cell/Module Production (MW)



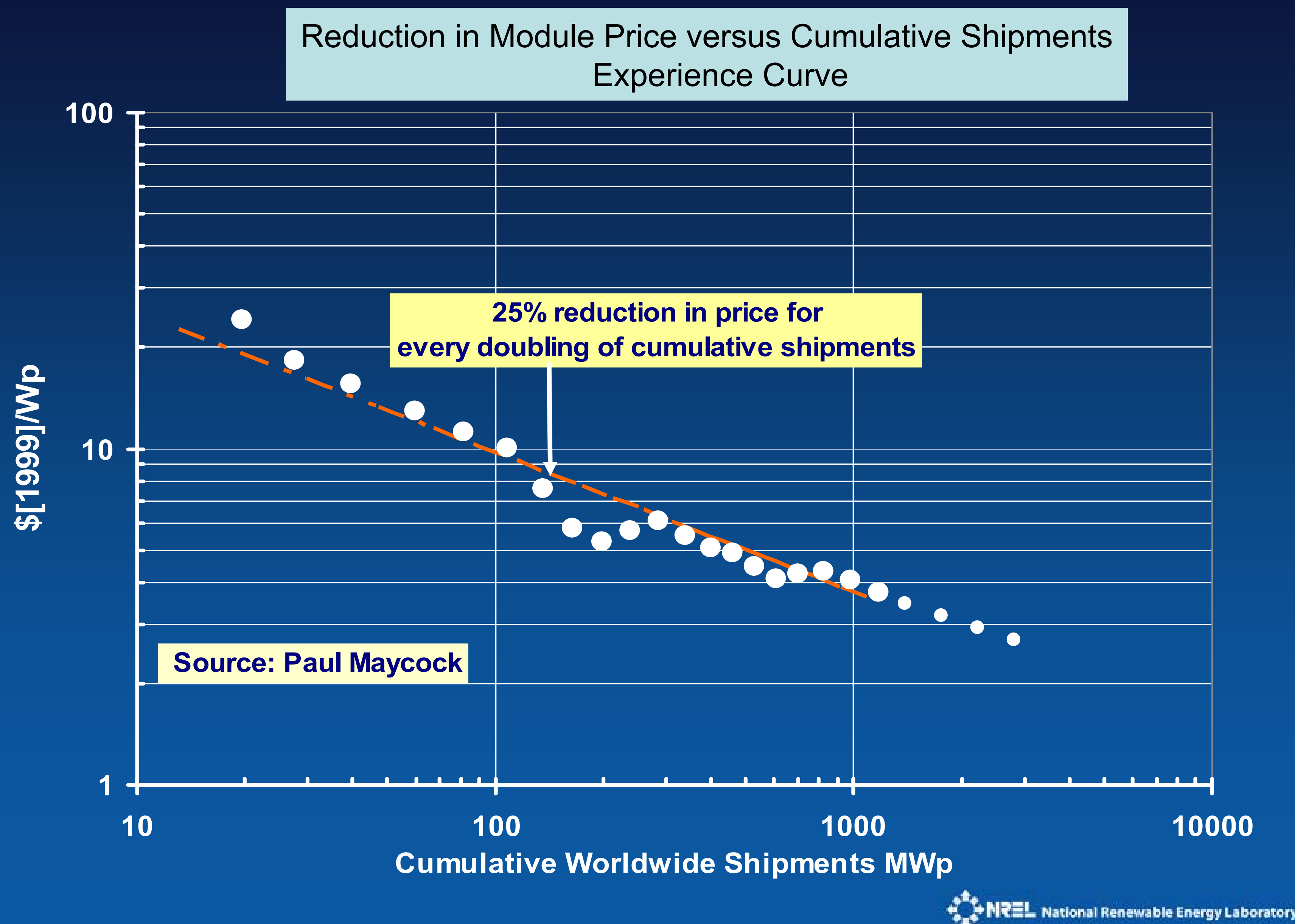
Source: *PV News*, March 2004

PV Manufacturing R&D Cost/Capacity



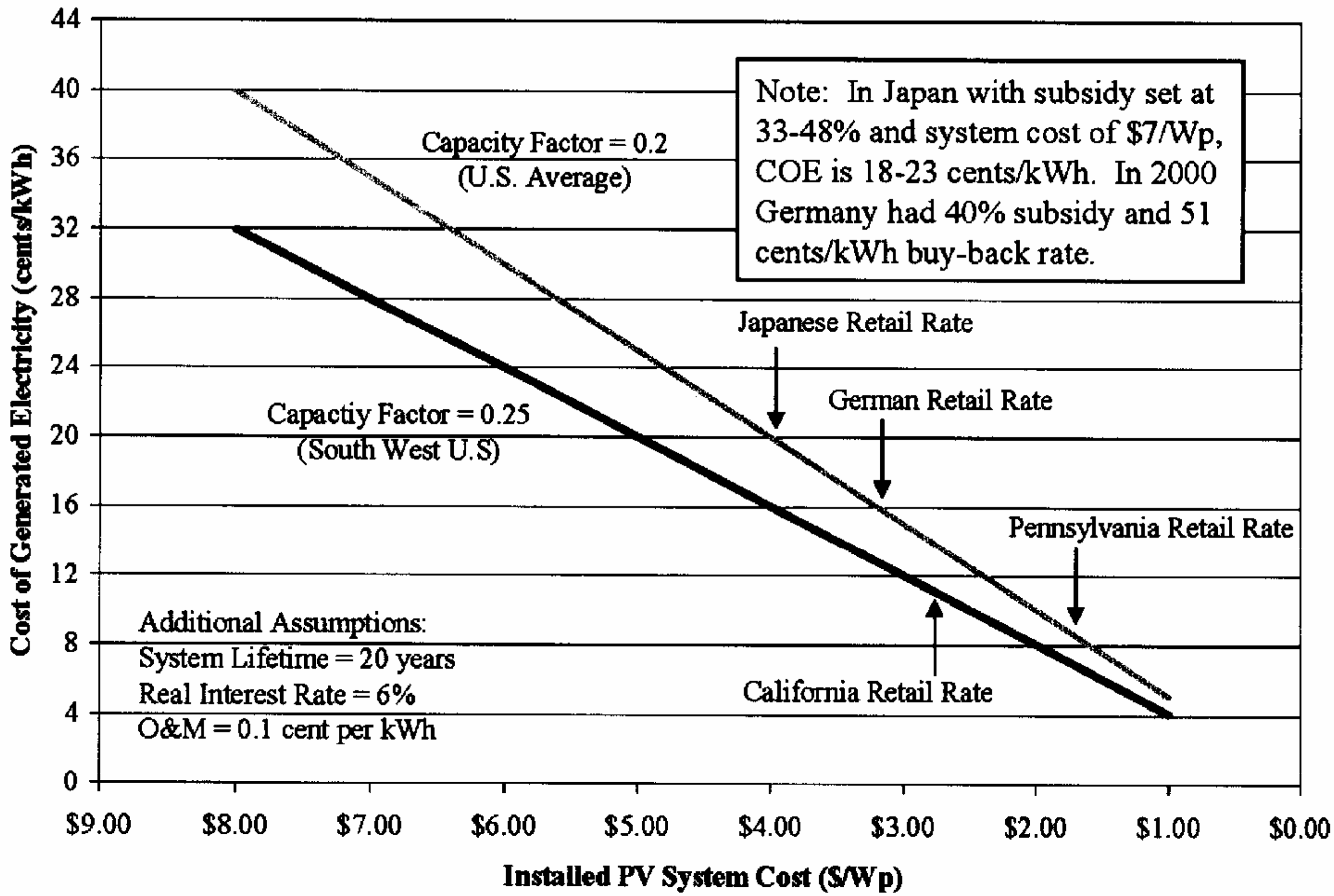
PV Manufacturing Research Data (DOE/U.S. Industry Partnership)

NREL National Renewable Energy Laboratory



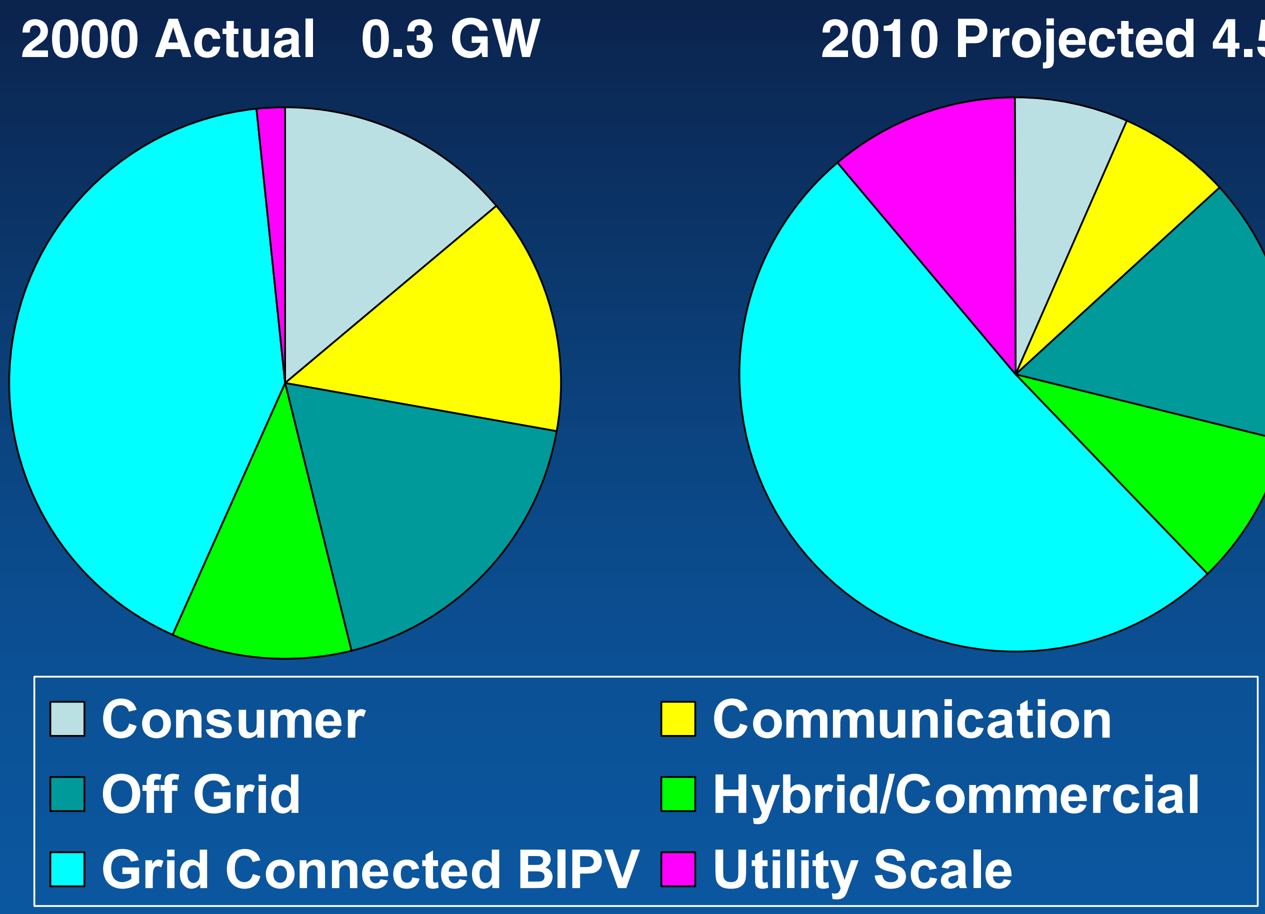
Reduction in Module Price versus Cumulative Shipments
Experience Curve
25% reduction in price for
every doubling of cumulative shipments
Source: Paul Maycock
$[1999]/Wp
100
10
1
10
100
1000
10000
Cumulative Worldwide Shipments MWp
NREL National Renewable Energy Laboratory

PV System vs. Electricity Costs

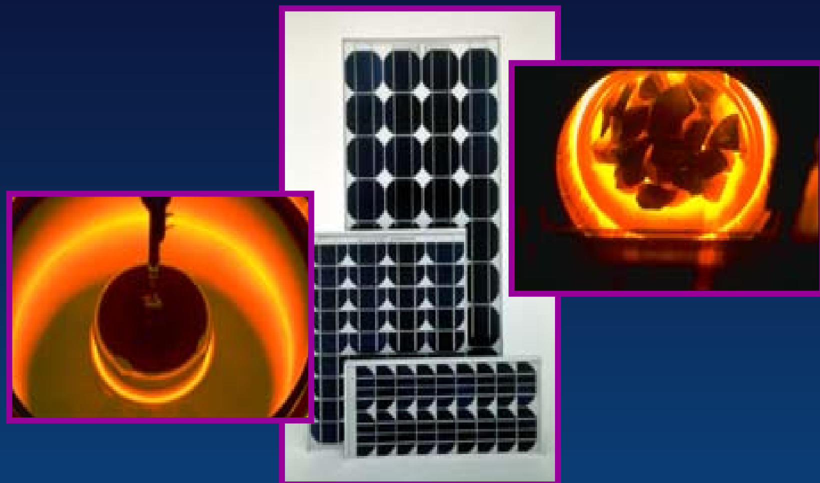


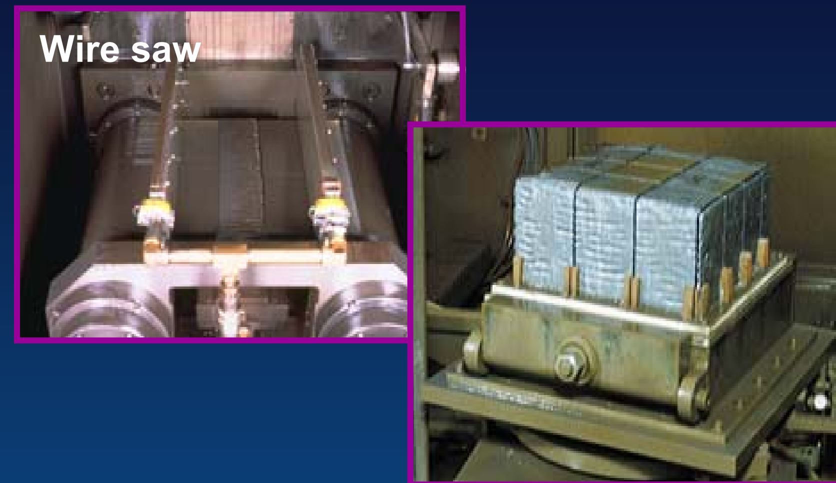
R. M. Margolis, NREL Presentation, March 24, 2003, page 15

PV Market Sectors



Crystalline Silicon (Ingot-Based) PV





- **Key companies:** Shell Solar, BP Solar, GE, Sharp, Kyocera, Sanyo, Motech, Cypress-SunPower
- ~85% of today's market
- ~800 MW capacity (to double in near-term)
- Proven products, 20-25 year warranties
- Large ingots: 100 kg CZ, 250 kg casting
- Multiple ingot growth with melt replenishment
- Wire saw: < 250 µm wafers, < 200 µm kerf

Efficiency Status	**Cells**	**Modules**
Float-zone	24.7	22.7*
Czochralski	22.0	13–17
Cast poly	19.8	10–16

- Batch/continuous processing
- High-efficiency devices in production
- Well-developed technology base--new understanding of defects/impurities

* Best prototype

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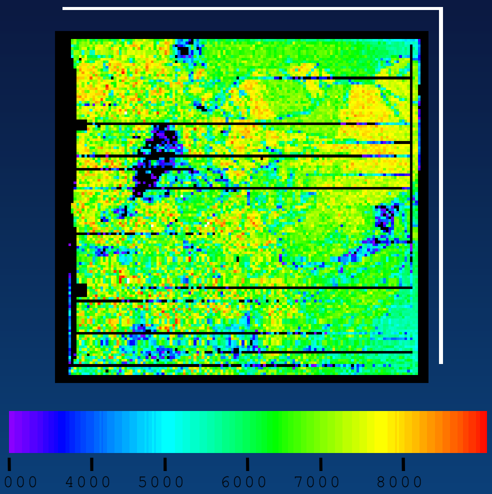
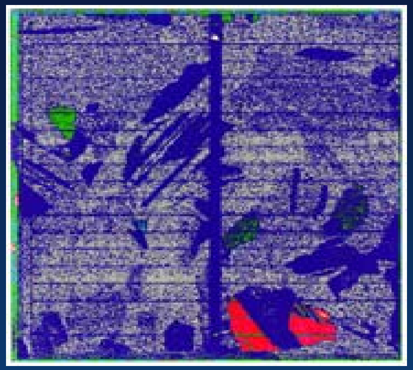
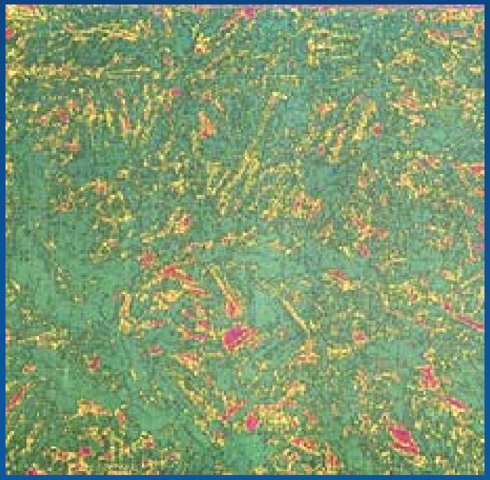
Light Induced Current Map



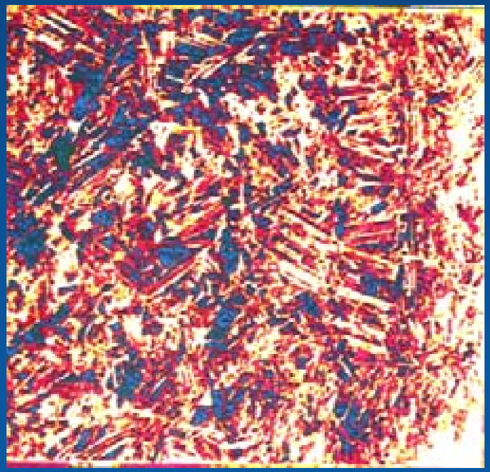
Reflectance Map



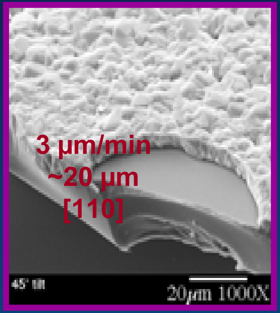
Dislocation Map

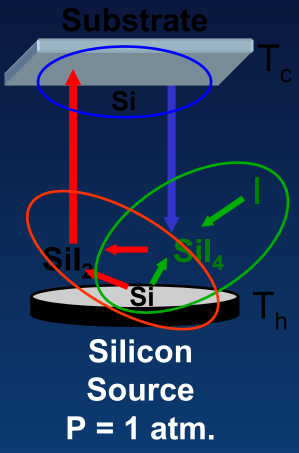


Grain Boundary Map



Crystalline Silicon (Non-Ingot-Based) PV





- **Key companies:** RWE Schott Solar, Evergreen Solar, GE, Pacific Solar, Kaneka
- Status varies from prototype modules to pilot production to commercial products (many MW)
- Proven products (~ 6% of market)
- Capacity increases underway—many tens of MW in near term
- Improved performance from defect/impurity and passivation studies
- Increasing interest in thin silicon growth

• Efficiency Status	Cells	Modules
EFG	14–16	11–13
String ribbon	14–16	10–12
Thick Si/substrate	16.6	9–10
Thin Si/substrate	5-12*	~ 7**

*Depends on process (some efficiencies not verified)

** Best prototype

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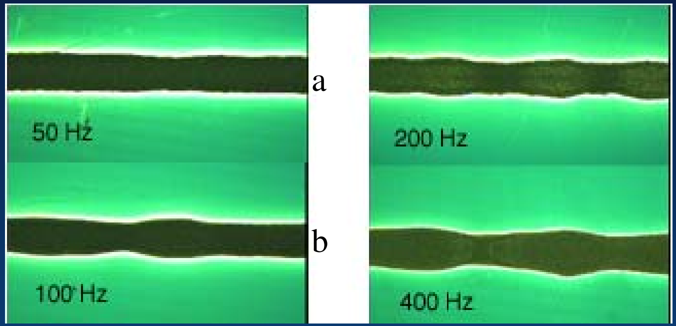
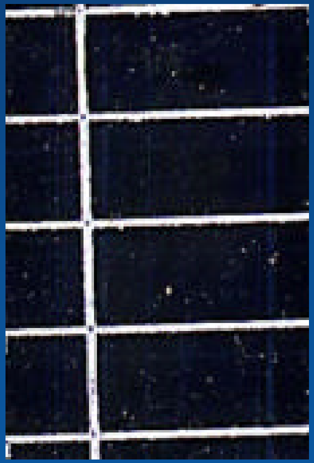
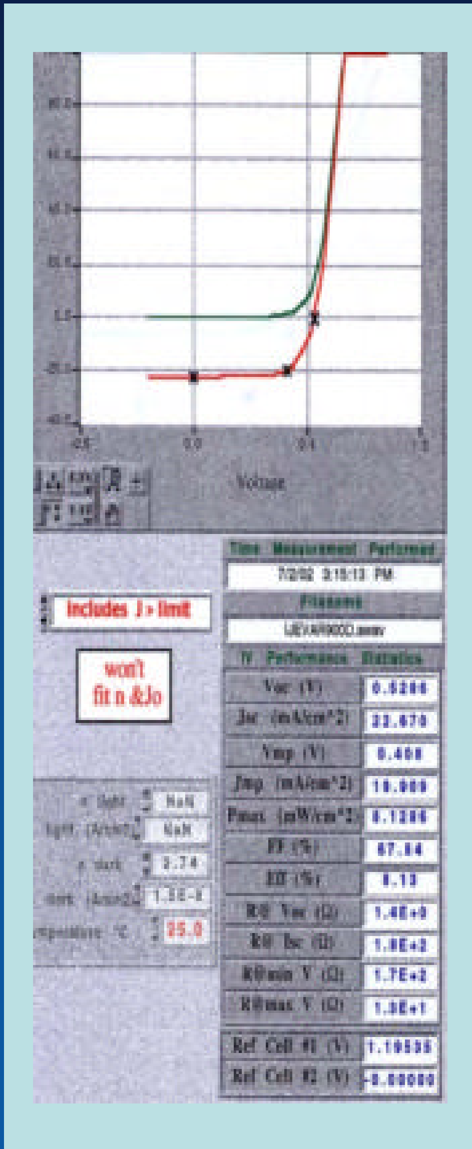
Ink Jet Printing of Ag and Cu contacts for Si Solar Cells 8% Cells on Si_3N_4



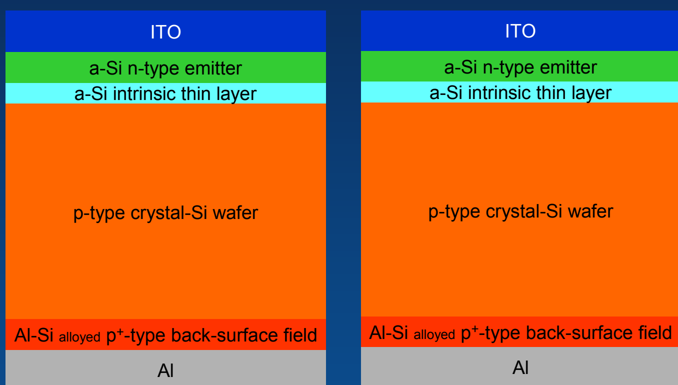


Line thickness: 15 µm
Line width: 250µm
Dep. temperature : 180 ^{o}C
Ann. temperature: 850 ^{o}C
Substrates from Evergreen Solar



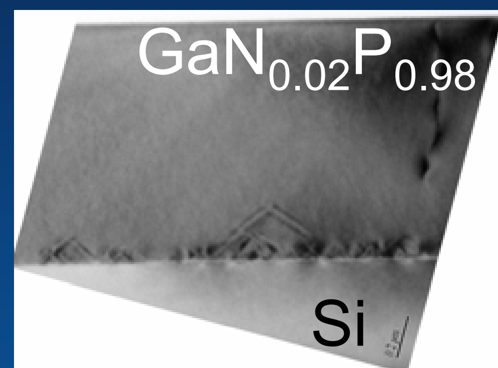
Building Higher Efficiency onto the Expanding Infrastructure for Silicon PV

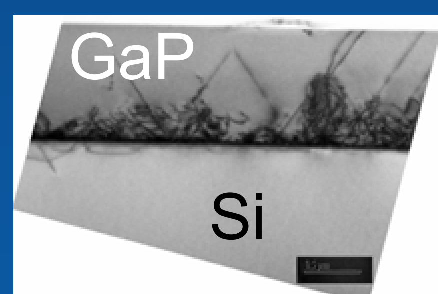
Heterojunction a-Si/c-Si cell
Potential >20% Efficient

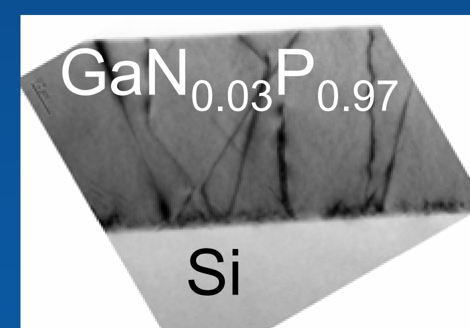


14.17 %
Best V_{oc}=628 mV (p-type CZ cell record)

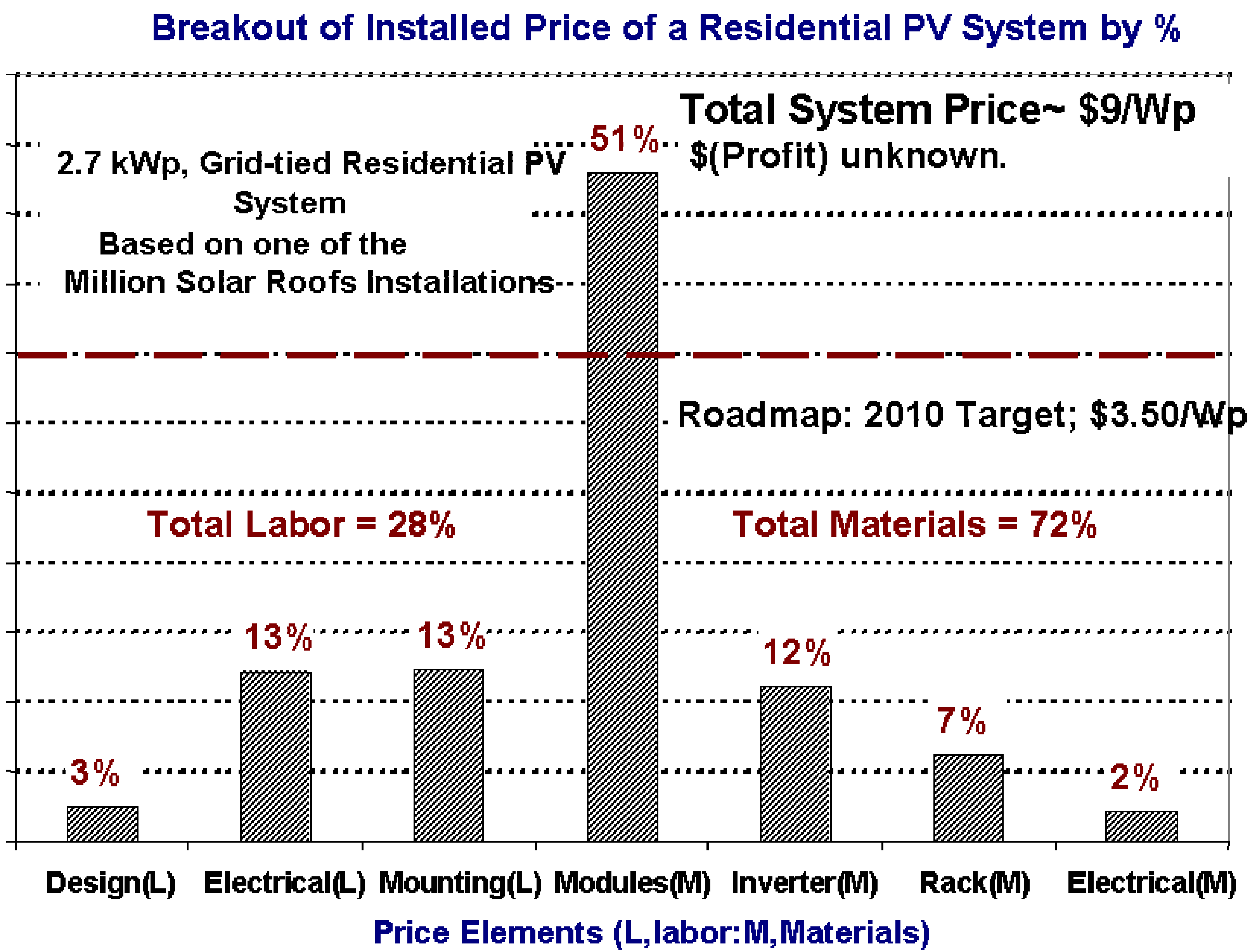
GaNP on Si Tandem
Potential >30% Efficient







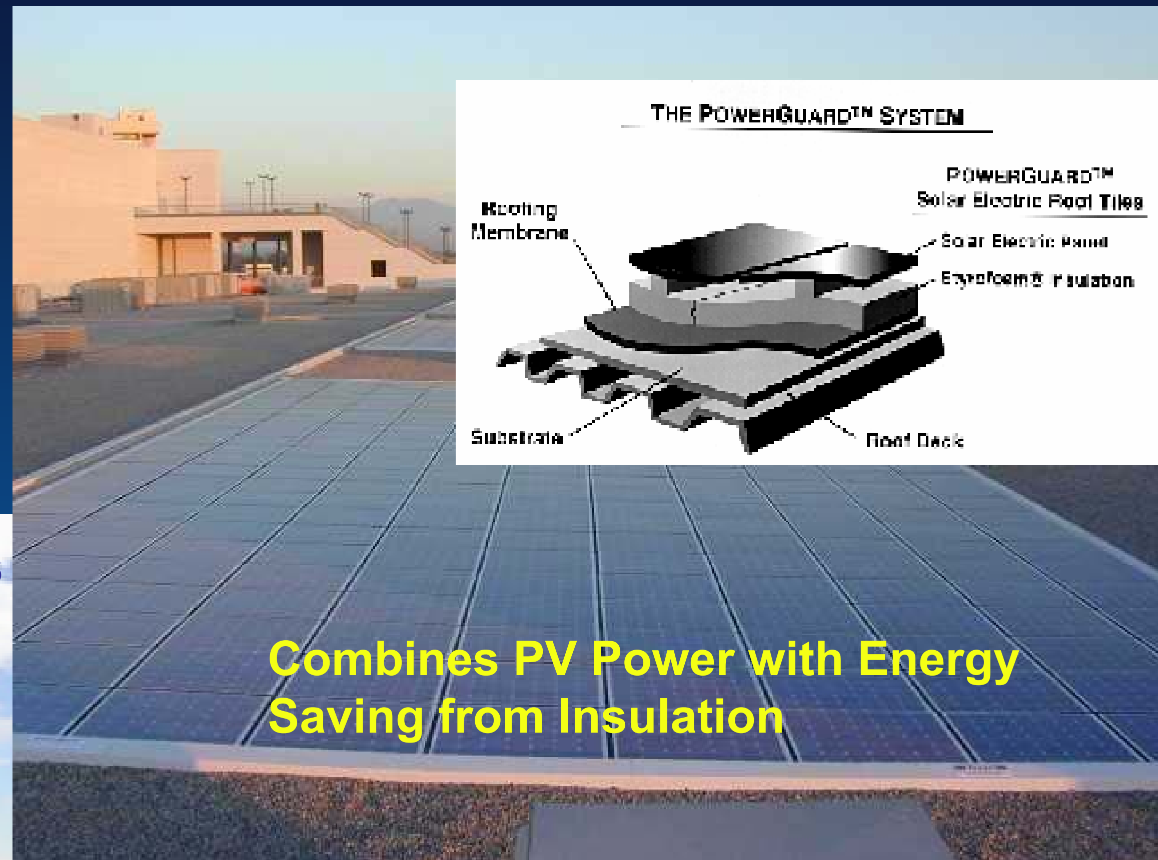
Conventional PV Installations



Breakout of Installed Price of a Residential PV System by %
Total System Price~ $9/Wp
$(Profit) unknown.
2.7 kWp, Grid-tied Residential PV System
Based on one of the Million Solar Roofs Installations
51%
Roadmap: 2010 Target; $3.50/Wp
Total Labor = 28%
Total Materials = 72%
3%
13%
13%
12%
7%
2%
Design(L)
Electrical(L)
Mounting(L)
Modules(M)
Inverter(M)
Rack(M)
Electrical(M)
Price Elements (L,labor:M,Materials)

Powerlight Roof Integrated PV System

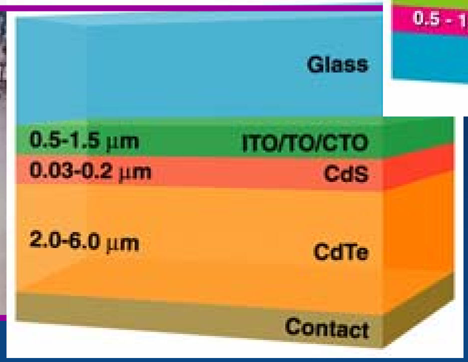
Advances in PV System Design Can Also Achieve Cost Advantages

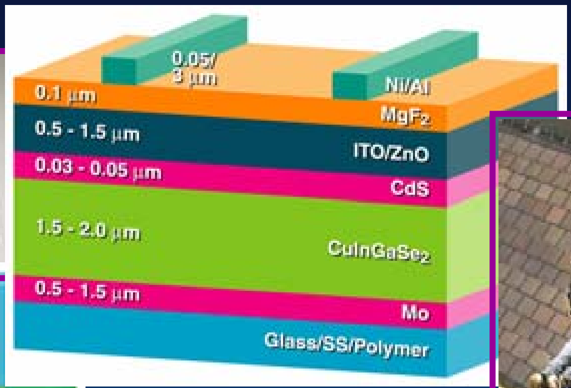


Combines PV Power with Energy Saving from Insulation

United Solar Shingles

Thin-Film PV





Key companies: United Solar/ ECD, Shell Solar, EPV, Global Solar/ITN, First Solar, Iowa Thin Films, HelioVolt, Wurth Solar, Showa-Shell, DayStar, Miasolé

- Multi-MW/year in consumer products
- 5 and 10 MW plants operational; few tens of MW in near term
- Unique products for building integration

Efficiency status:

Cell	12-19
Submodule	10-12
Module	7–11
Commercial	5–10

- Understanding of film growth, microstructures, defects, and device physics
- Reproducible high-efficiency processes
- Multiple junctions

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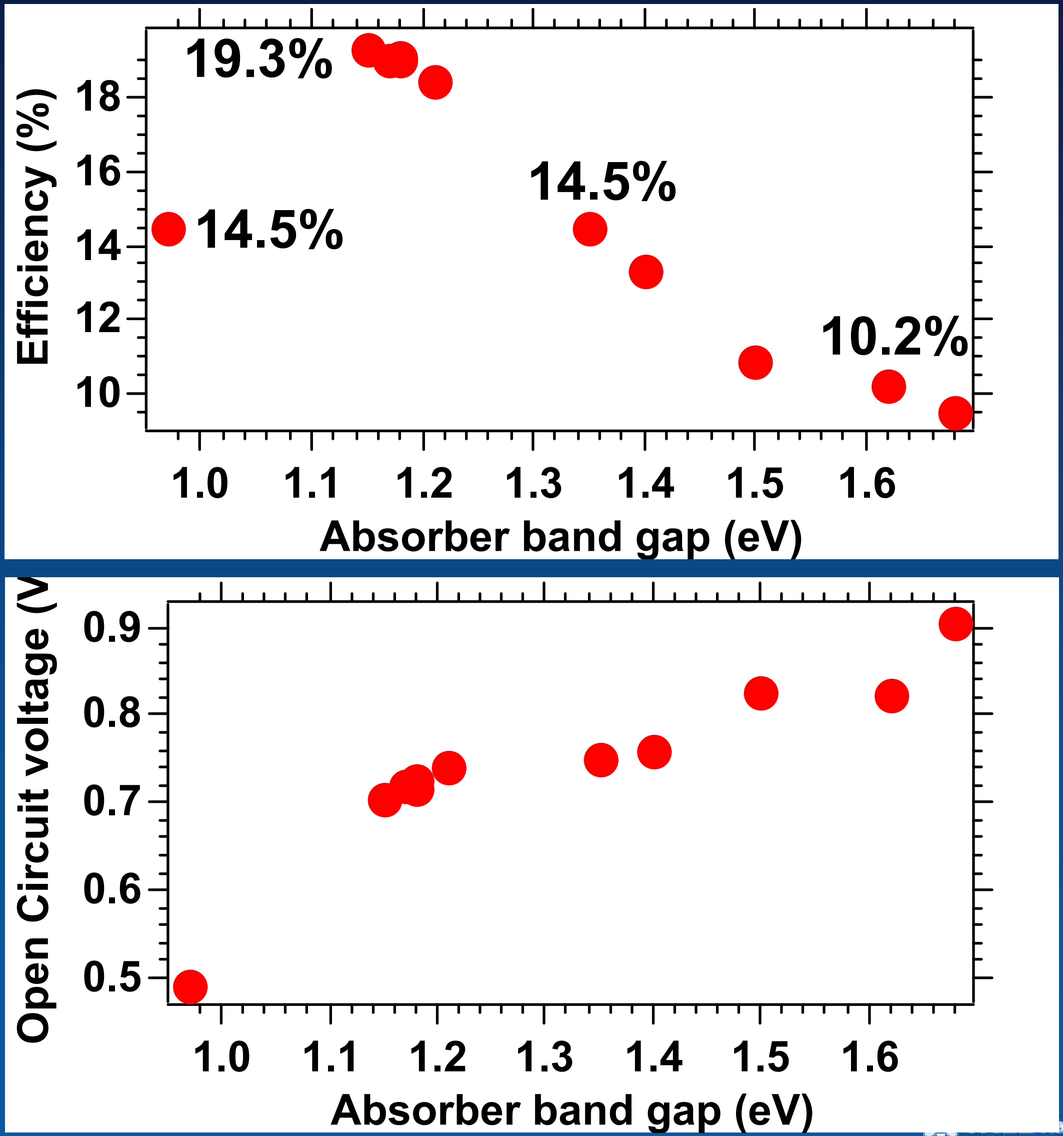
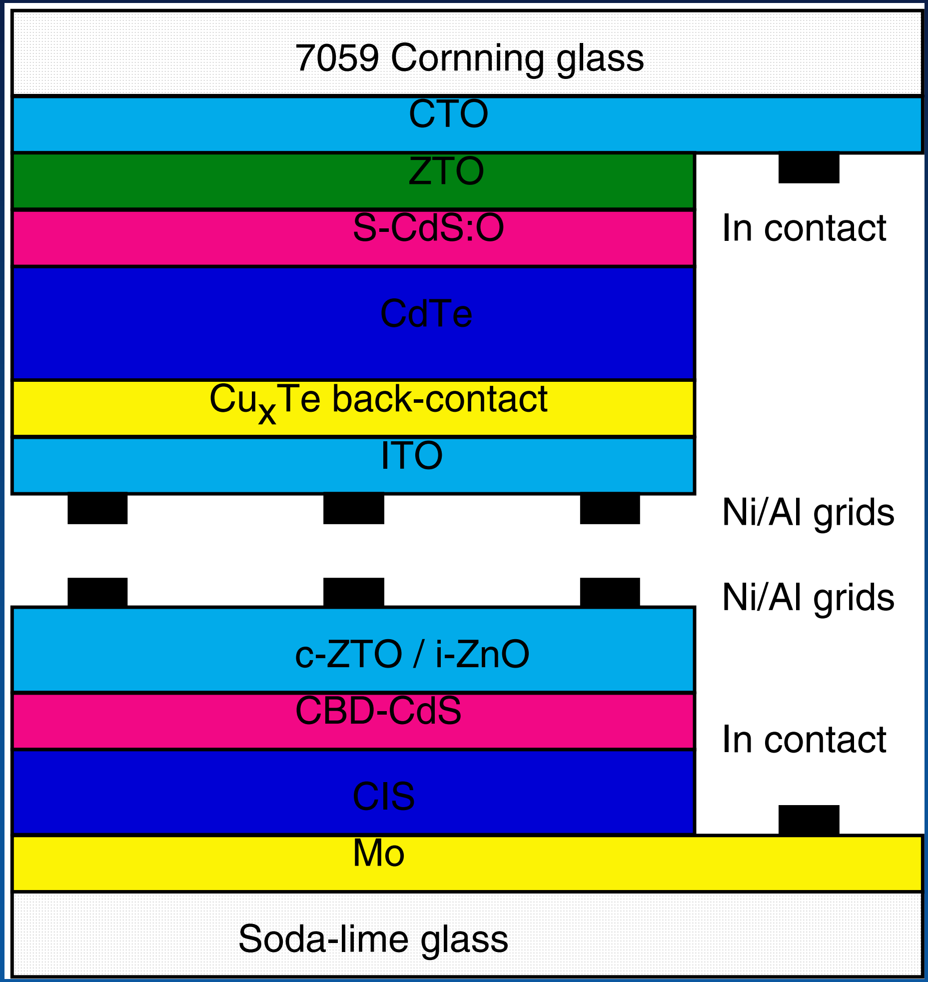
CIGS Performance Across the Entire Compositional Range for Tandem Cells



Polycrystalline Thin Film Tandem Solar Cell

CdTe top cell
Achieved 50% transmission, 12.7% efficiency

CIS bottom cell
Achieved 14.5% efficiency

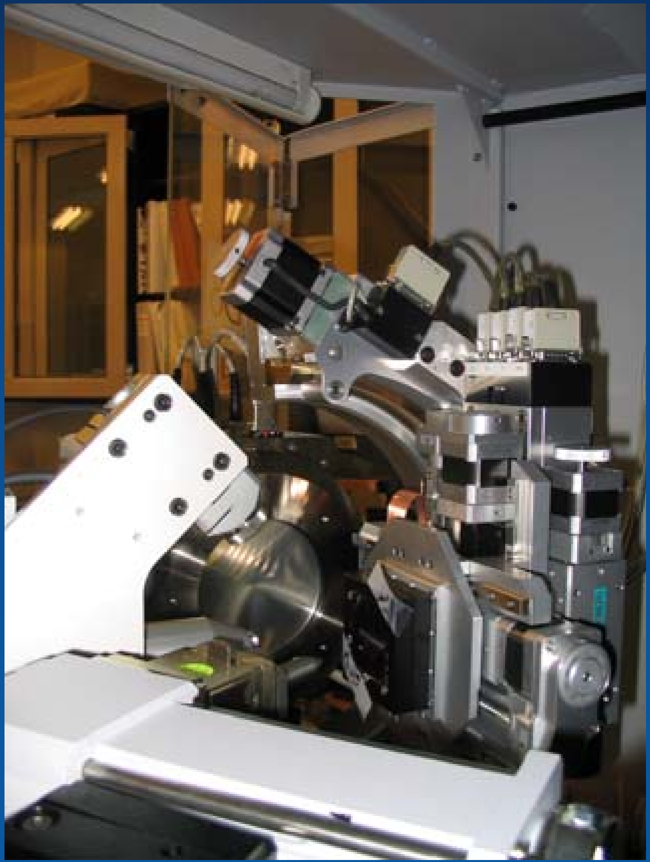


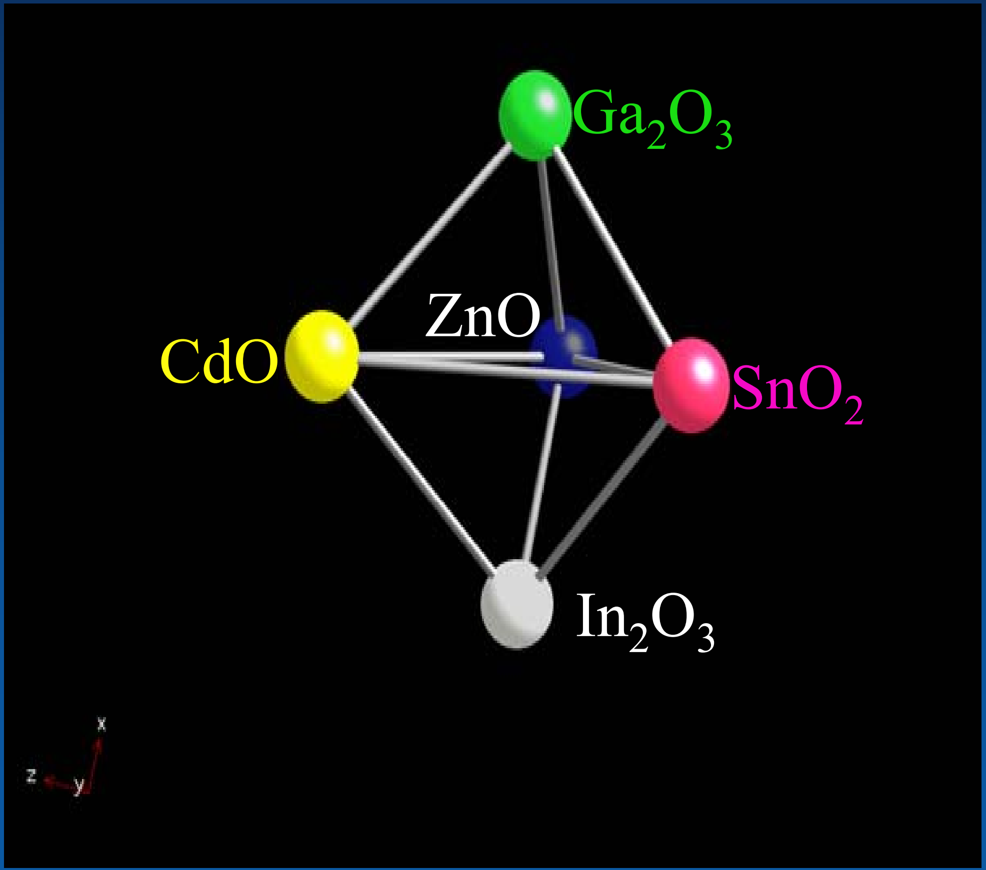
FY06 milestone: 15% efficient 4-terminal device will be met one year early

Accomplishments: High Throughput Methods

Developing Capabilities for Combinatorial Materials Science at NREL

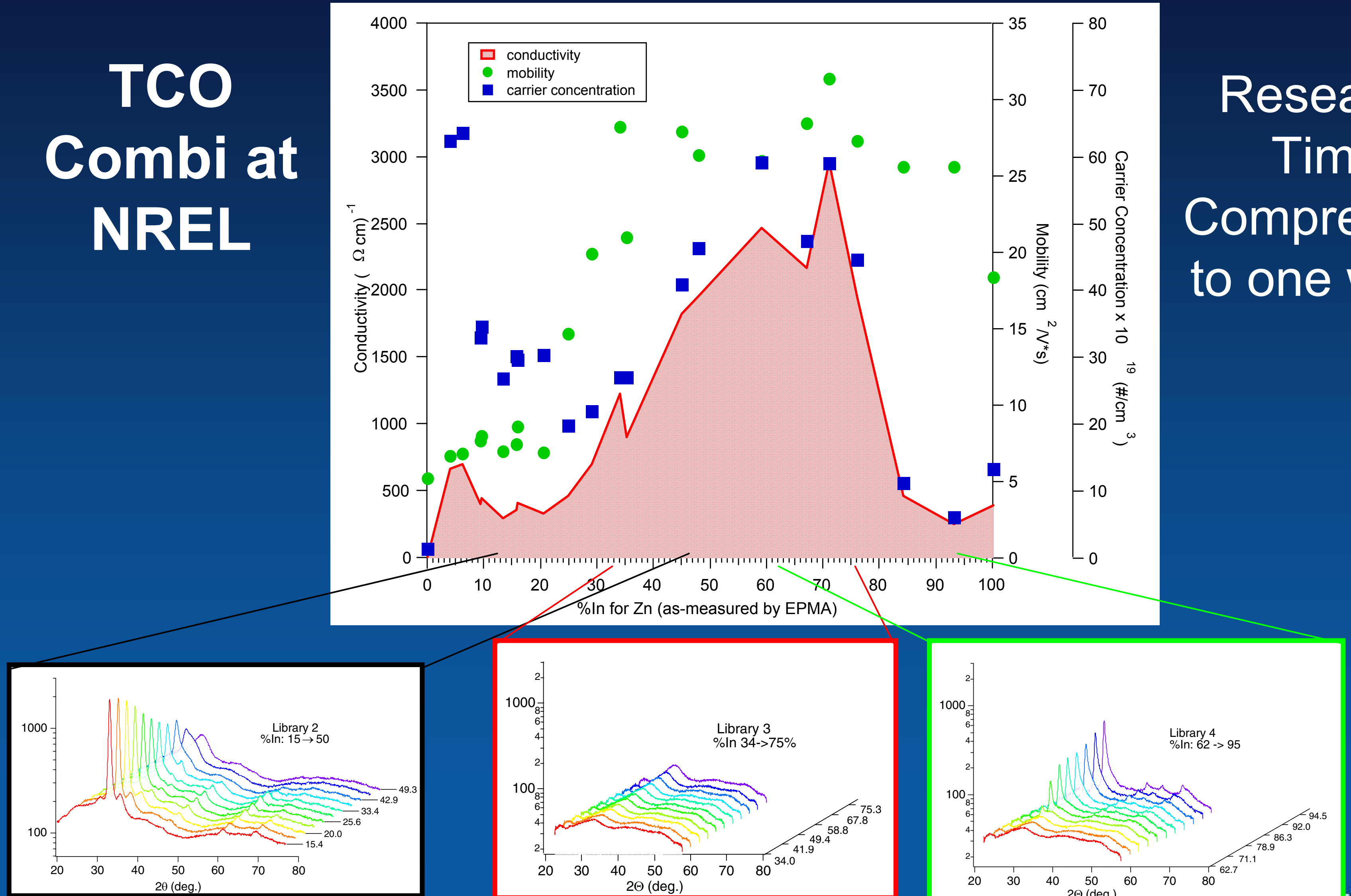
Combinatorial, Focused-Beam X-ray Diffraction





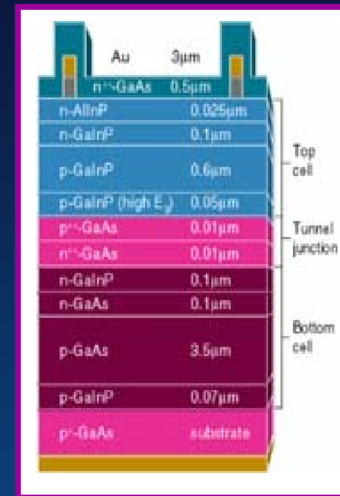
High Throughput Research Methods

TCO Combi at NREL



Research Time Compressed to one week

High-Efficiency and Concentrator PV



Key companies: Amonix, Spectrolab, Emcore, Sunpower, ENTECH; Solar Systems ltd

- Manufacturability demonstrated
  - Low-concentration, line focus
  - High-concentration, point focus
  - High efficiency cells (Si, GaAs, multijunctions) in production
- Limited applications in today's markets
  - Hydrogen generation may be well matched

Efficiencies:

Si (up to 400X)	**27**
GaAs (up to 1000X)	**28**
GaInP$_2$/GaAs (1X)	**30.3**
GaInP$_2$/GaAs (180X)	**30.2**
GaInP$_2$/GaAs/Ge (40–600X)	**36.9**

- Module efficiencies: 15-17% (Si); best prototypes: >20% (Si), >24% (GaAs), 28% (GaInP$_2$/GaAs/Ge,10X)
- Large space markets drive GaInP$_2$/GaAs and GaInP$_2$/GaAs/Ge commercial cell production

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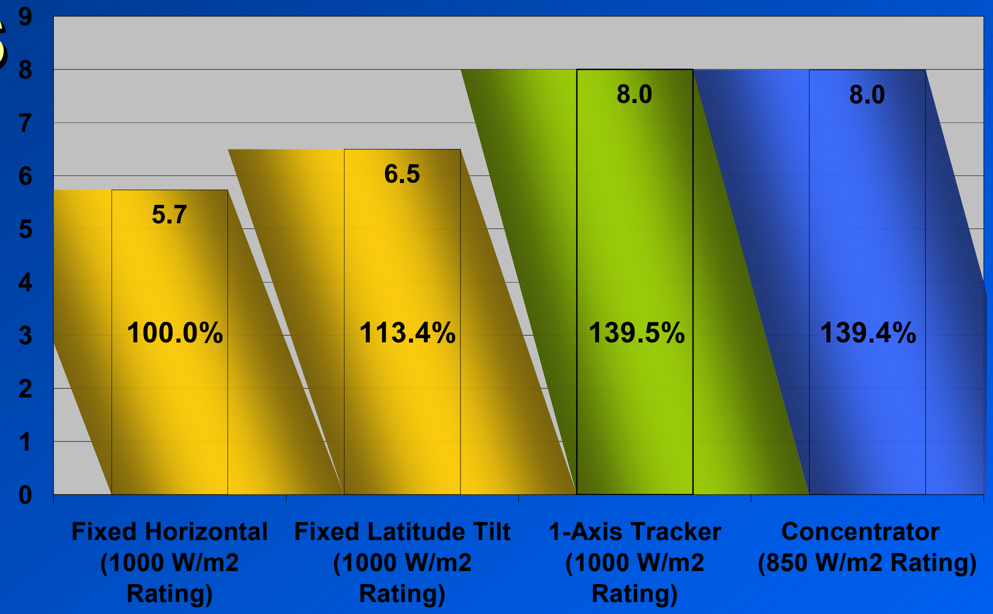
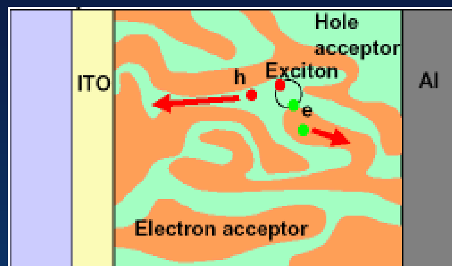
Solar Tracking Provides Energy Benefits

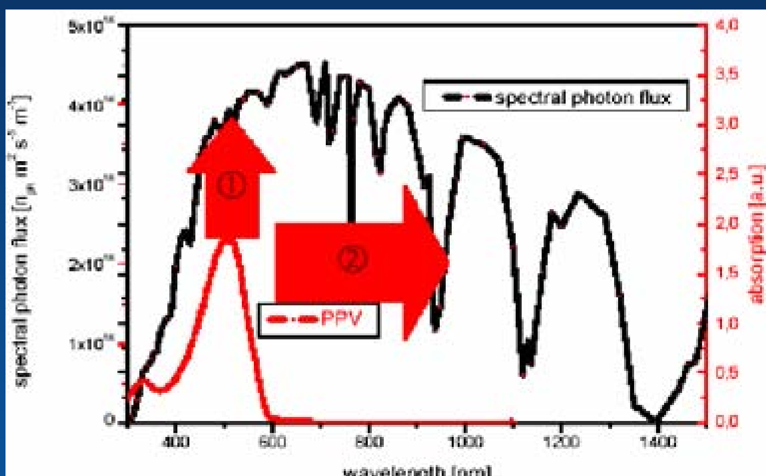


- Tracking systems provide 15 to 20% more energy than fixed PV
- Up to 40% more than fixed horizontal systems

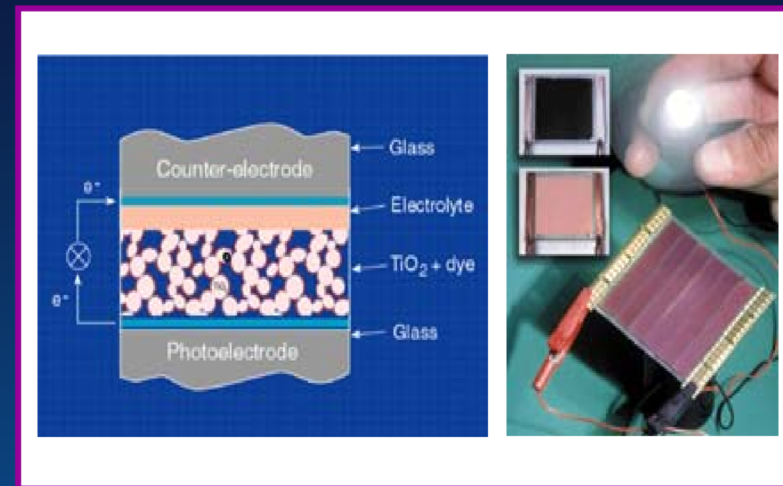
Novel Concepts, Excitonic Devices and New Materials

- Key Companies: GE, Kodak, Konarka, NanoSolar, NanoSys, Luna, UltraDots …





Light management	• Enhanced absorptivity of dyes • Low bandgap polymers
Reduce series resistance	• Higher mobility polymers • Enhanced TCOs • Electrolyte formulations • Polymer morphology



- **Dye-sensitized TiO_2 photochemical cells**
- Potential for very low cost
- Nanocrystalline TiO_2, with monolayer dye sensitizer,in liquid electrolyte
- 11%-efficient cell; scale-up for consumer products underway
- Dye stability issue
- Gel or solid-state electrolytes in research
- Photoelectrochromic window (with WO_3)

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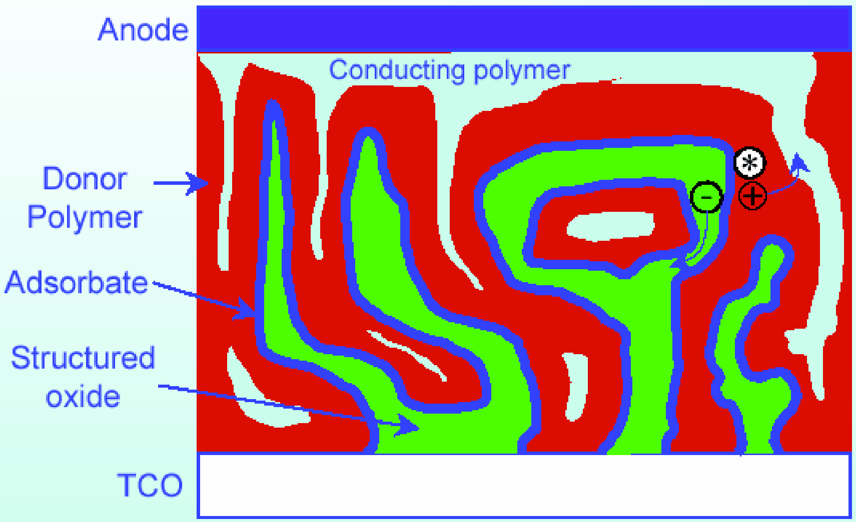
Accomplishments: Discovery

Organic Solar Cells

Nanostructured Oxides – Polymer Composites

2-d slice of a nanostructured device concept:



Multistep charge transfer at interface:

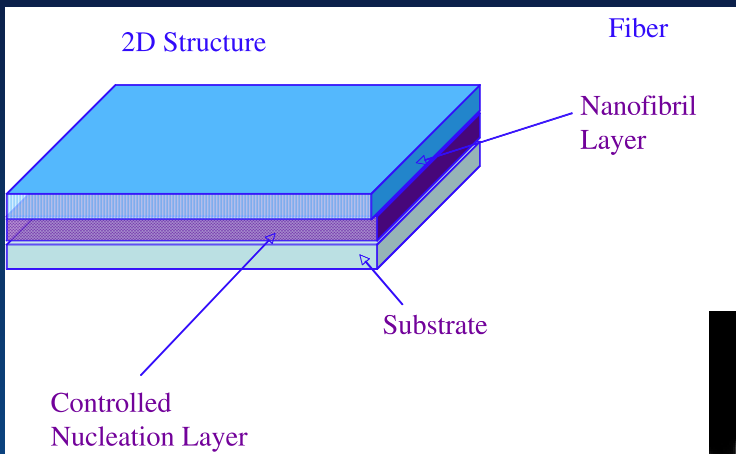
1) polymer* + adsorbate $\longrightarrow$ polymer$^+$ + adsorbate$^-$

2) adsorbate$^-$ + oxide $\longrightarrow$ adsorbate + oxide$^-$

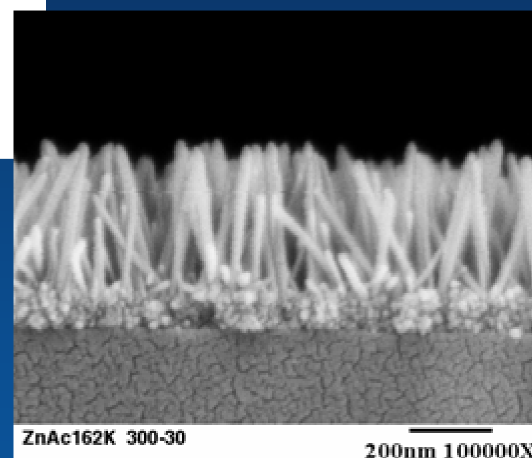
Strengths:

- Long optical path-length
- Short carrier-to-electrode path-length
- Higher electron mobility
- No isolated clusters, guaranteed percolation
- Better adhesion between layers, mechanical durability

Controlled Nucleation Layers for Nanocomposite Organic Solar Cells

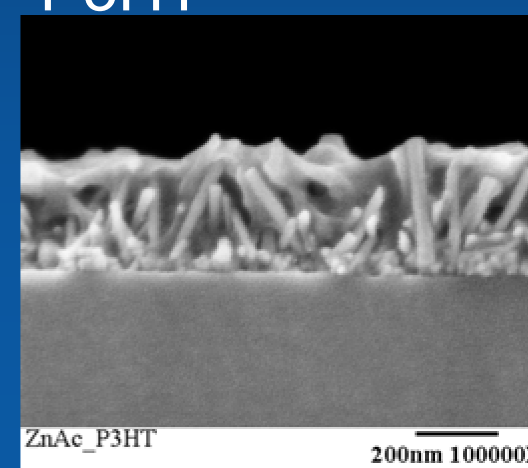


The Goal

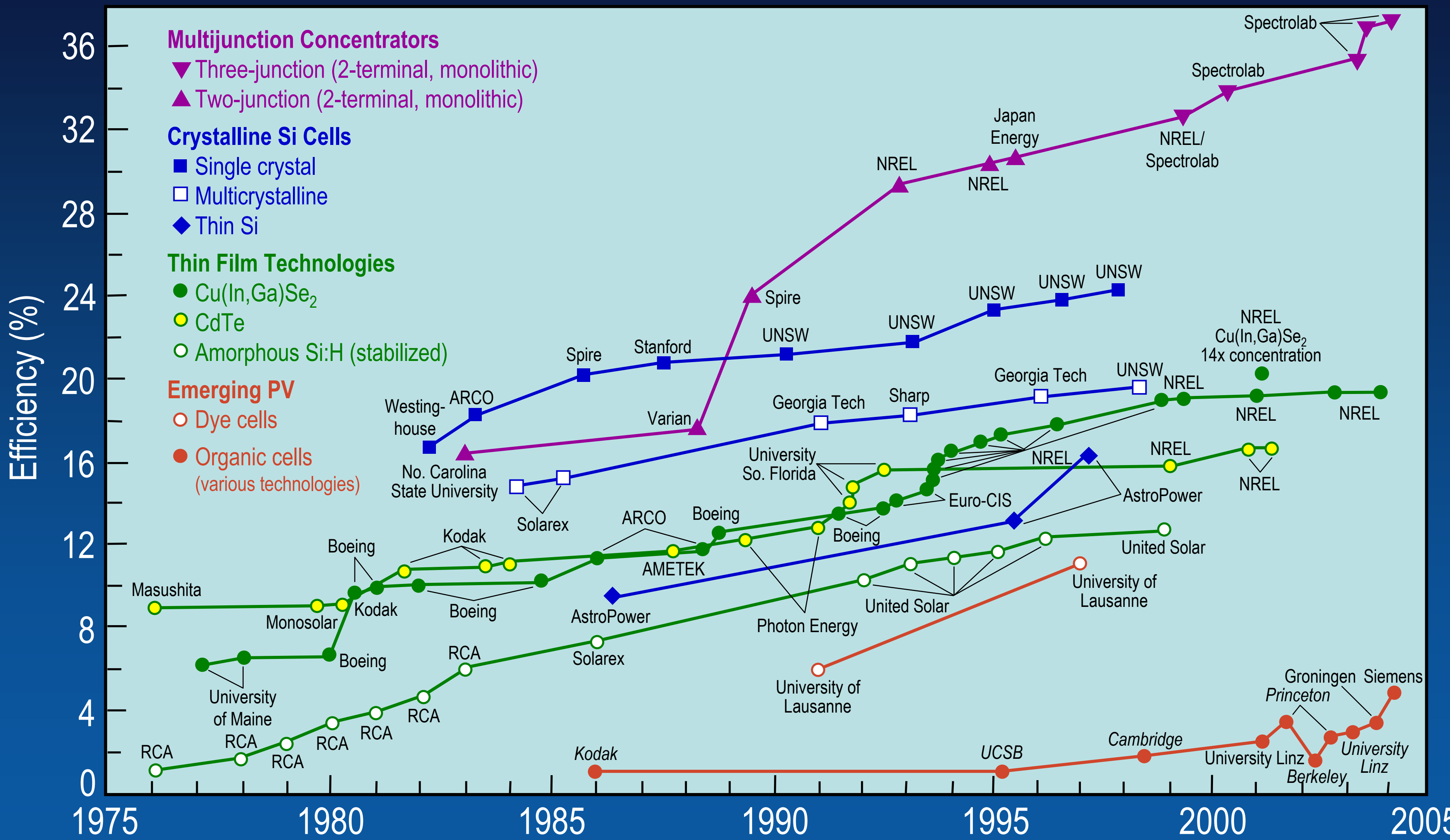


ZnO Nanofibrils

Wetted with P3HT



Best Research-Cell Efficiencies



NREL National Renewable Energy Laboratory

Solar Technologies Research and Applications

- Solar technologies maintain an aggressive learning curve and are cost competitive as alternative energy sources in a growing number of markets
  - Approaching retail electricity rates in Japan and Europe
- Low retail energy costs in the U.S. discourage manufacturing and deployment of new technologies
- Projected technology improvements can bring solar electricity generating costs to U.S. retail electric levels

Changing Energy Landscape

- Natural Gas Shortage
- Transmission and Distribution Limitations
- CEO's Call for National Energy Strategy
  - With Balance
- International Pressure on Global Climate Change
- State and Local Initiatives for Renewable Energy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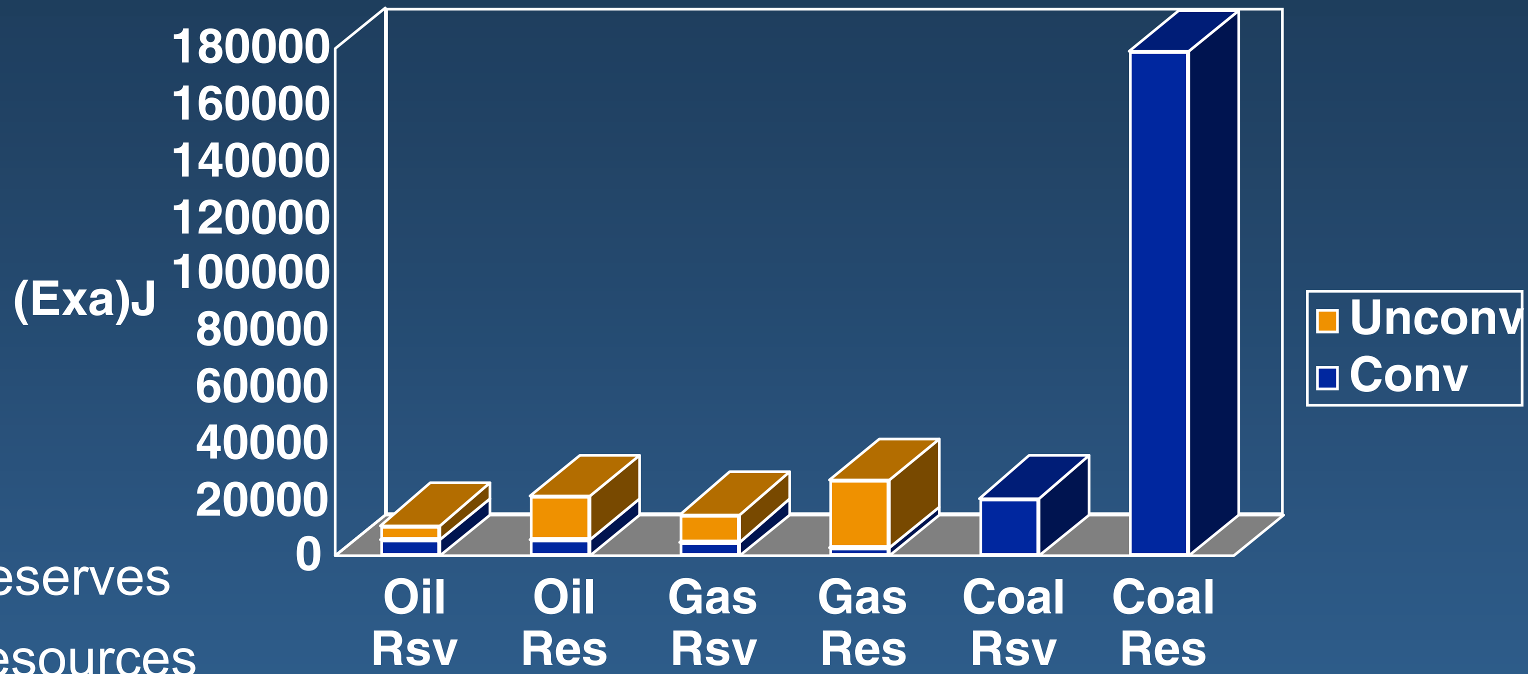
ISAT GeoStar 45
23:15 EST 14 Aug. 2003

Energy Reserves and Resources



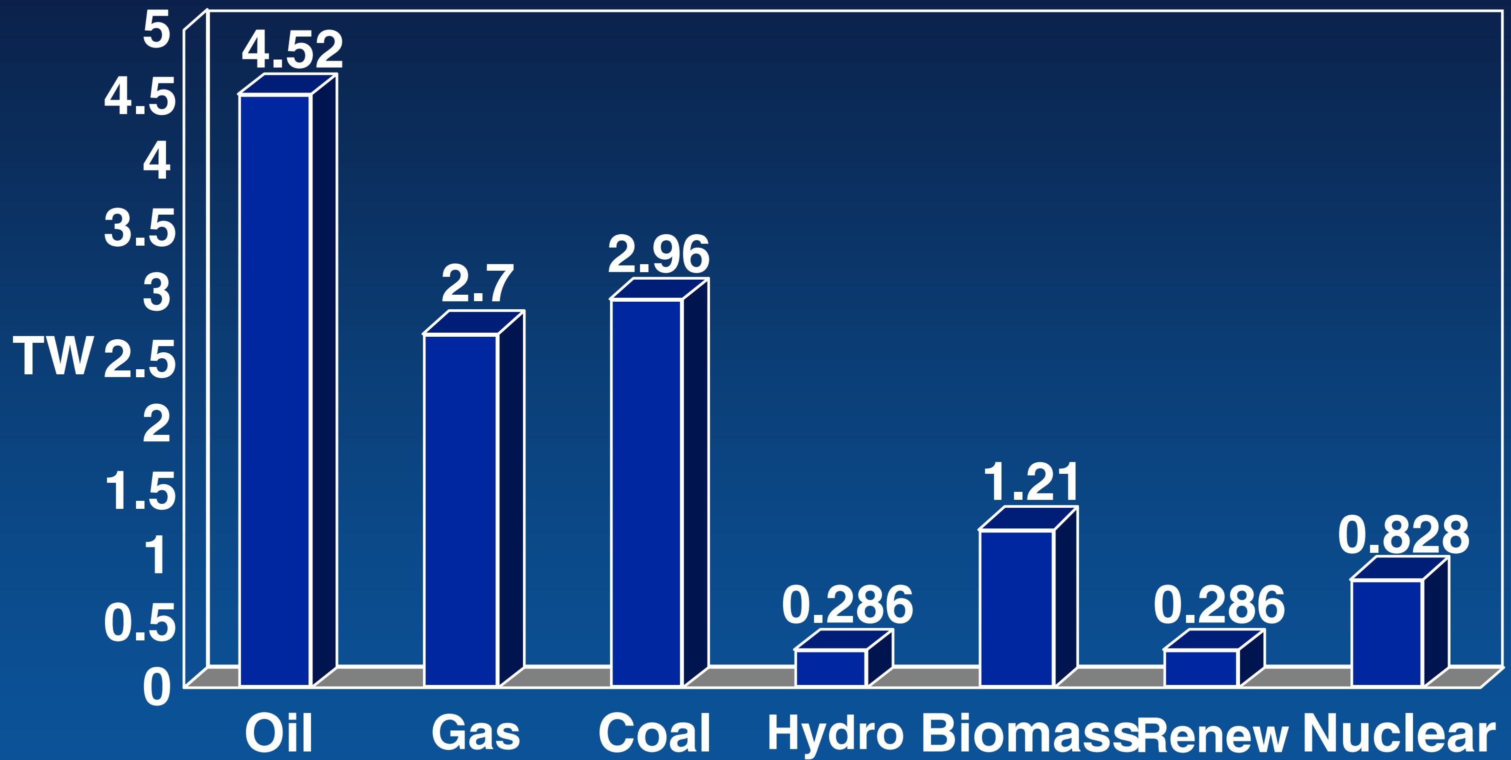
Rsv=Reserves

Res=Resources

	Reserves/(1998 Consumption/yr)	Resource Base/(1998 Consumption/yr)
Oil	40 - 78	51 - 151
Gas	68 - 176	207 - 590
Coal	224	2160

From: Nathan Lewis, Global Energy Perspective

Mean Global Energy Consumption, 1998



Total: 12.8 TW   U.S.: 3.3 TW (99 Quads)

From: Nathan Lewis, Global Energy Perspective

Sources of Carbon-Free Power

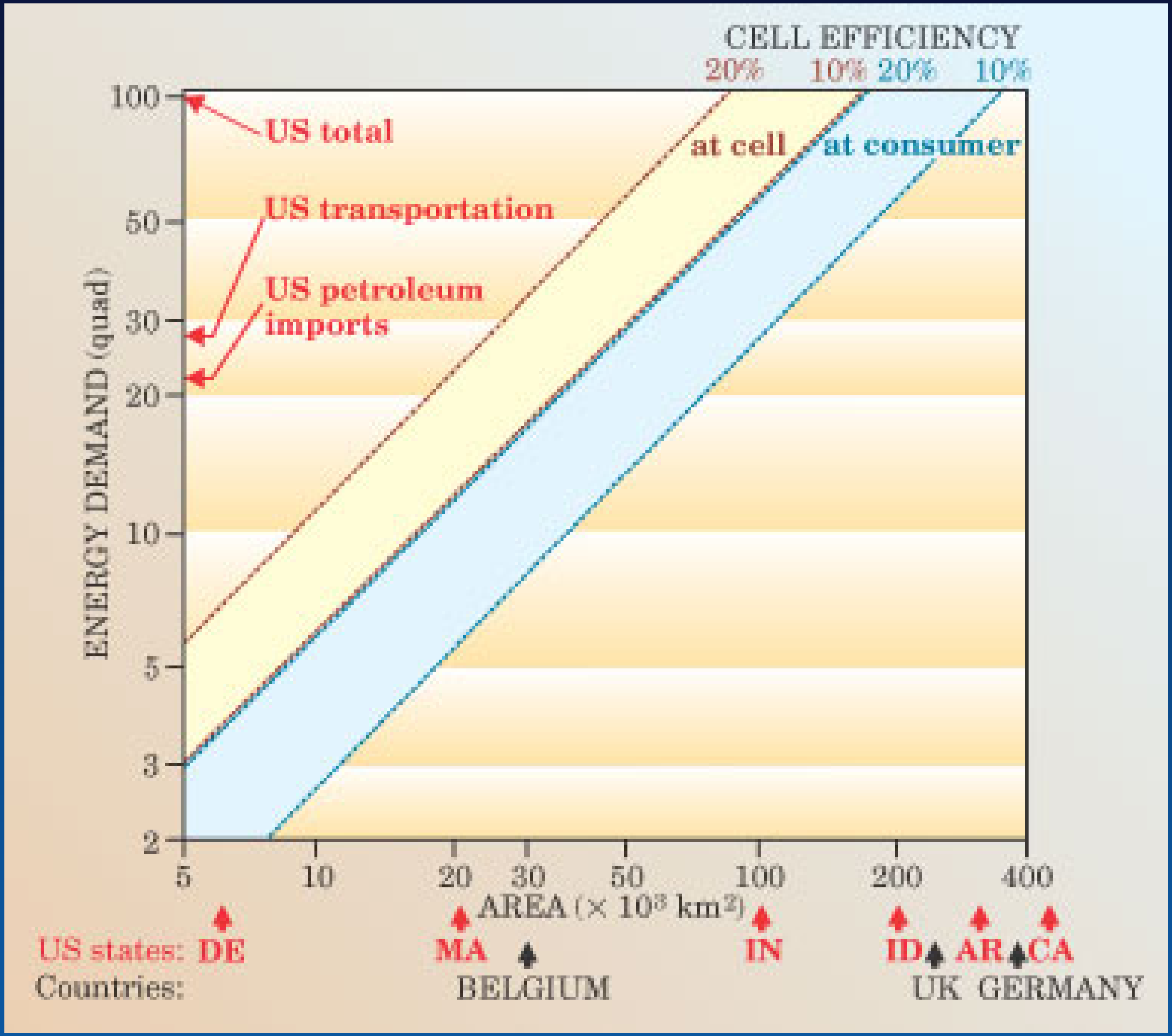
- Nuclear (fission and fusion)
  - 10 TW = 10,000 new 1 GW reactors
  - i.e., a new reactor every other day for the next 50 years

→ 2.3 million tonnes proven reserves; 1 TW-hr requires 22 tonnes of U
→ Hence at 10 TW provides 1 year of energy
→ Terrestrial resource base provides 10 years of energy
→ Would need to mine U from seawater (700 x terrestrial resource base)

- Carbon sequestration

- Renewables

From: Nathan Lewis, Global Energy Perspective



From: Paul B. Weisz, Physics Today, July 2004

Solar Land Area Requirements

From: Nathan Lewis, Global Energy Perspective

NREL National Renewable Energy Laboratory

Solar Cell Area Requirements to Meet Energy Demand in Select Countries

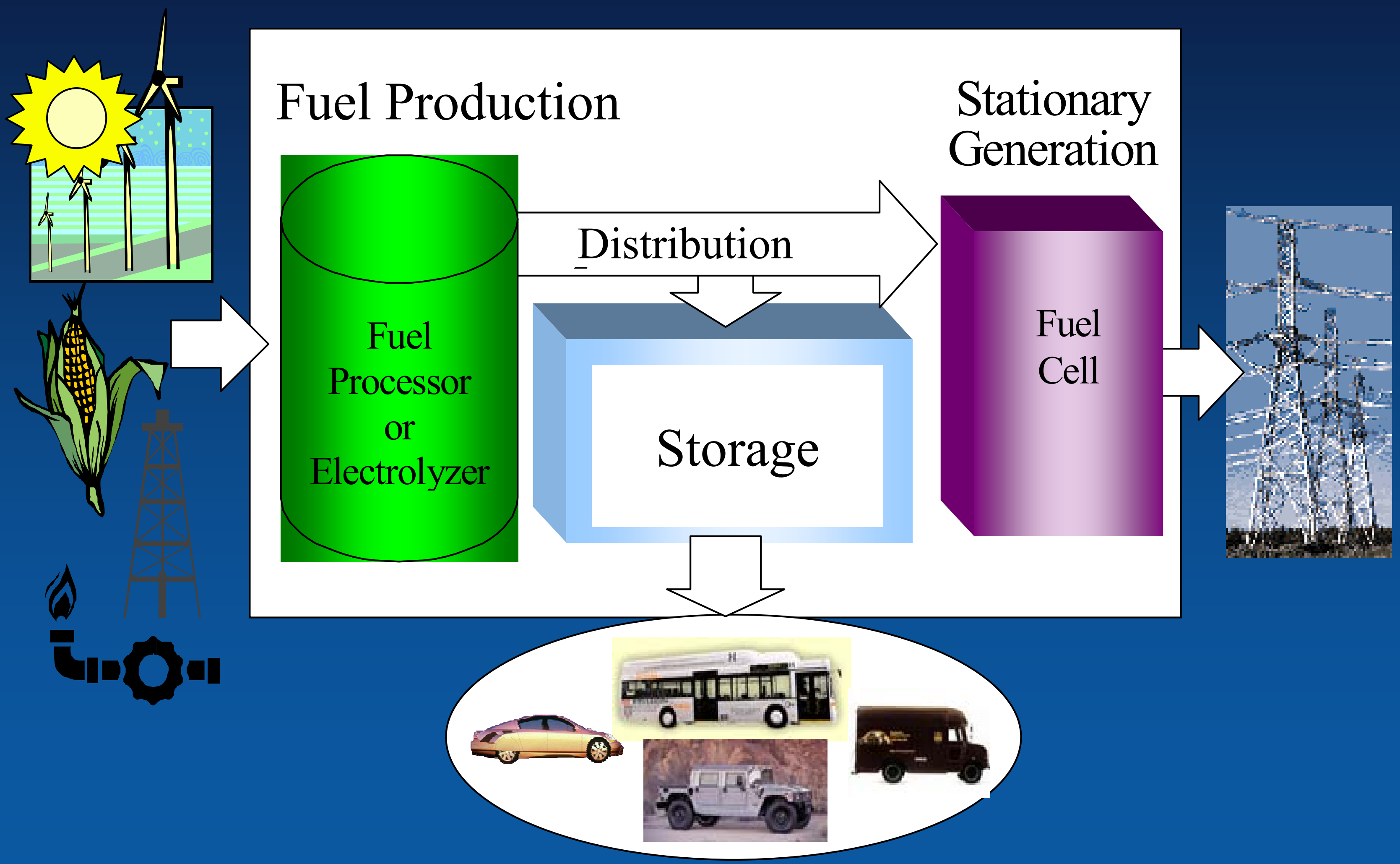
	Energy consumed per year*		Land area	Approximate solar cell area needed	
	Quads per 10^6 people	Total quads	10^3 km^2	10^3 km^2	% of land
US	0.36	100	9 591	263	2.7
Belgium	0.27	2.7	30	7	24.0
Australia	0.19	4.8	7 580	13	0.2
Russia	0.17	26	16 981	69	0.4
Japan	0.17	21.8	372	58	15.4
Germany	0.17	14	356	37	10.3
UK	0.17	10	243	26	10.8
France	0.17	10	546	26	5.0
Brazil	0.05	8.6	8 466	23	0.3
China	0.03	32	9 377	84	0.9
Egypt	0.03	2.0	996	5	0.5

*Data from Department of Energy/Energy Information Administration *International Energy Annual 1999.*

From: Paul B. Weisz, Physics Today, July 2004

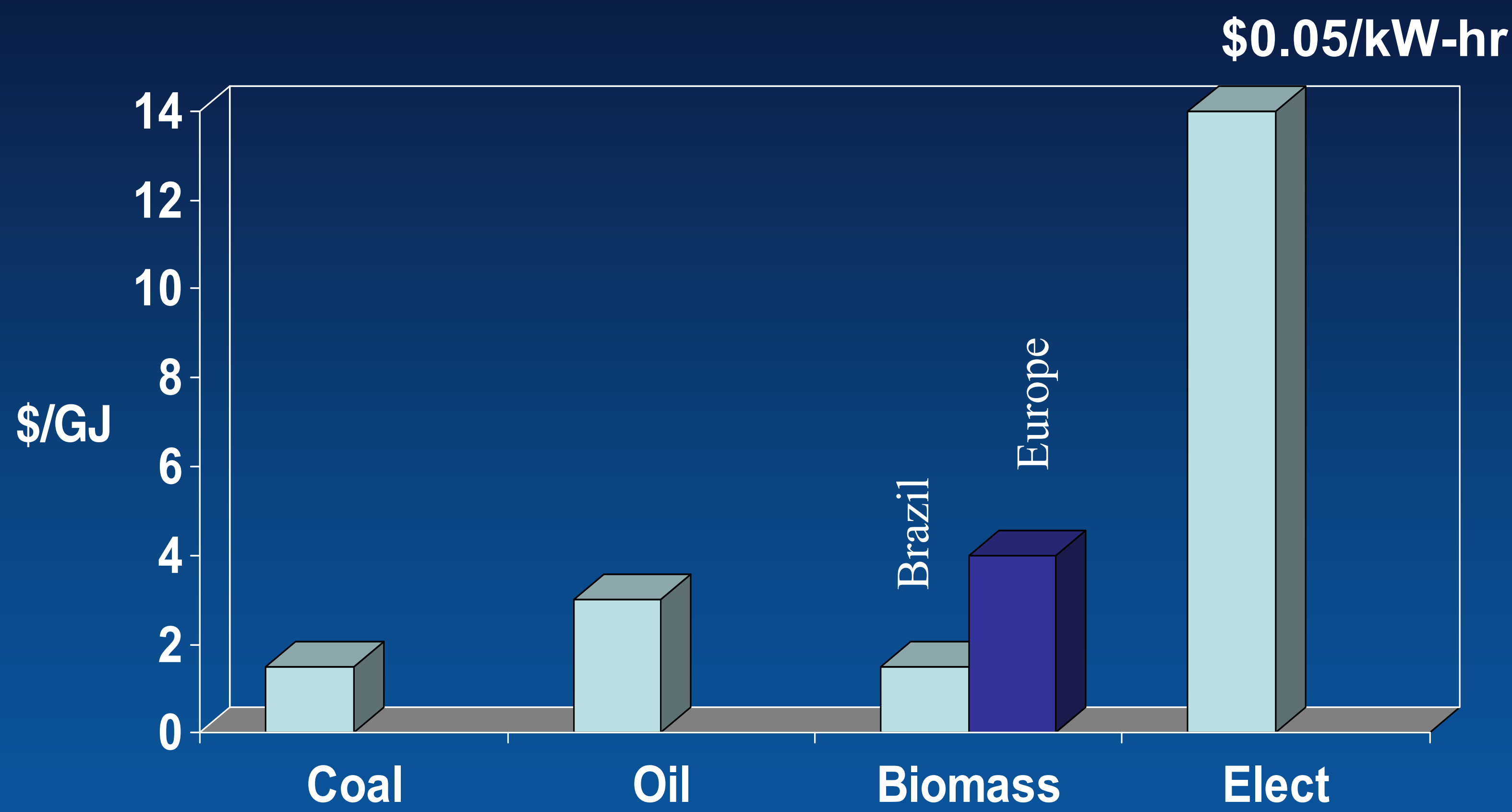
The Need to Produce Fuel

"Power Park Concept"



From: Nathan Lewis, Global Energy Perspective

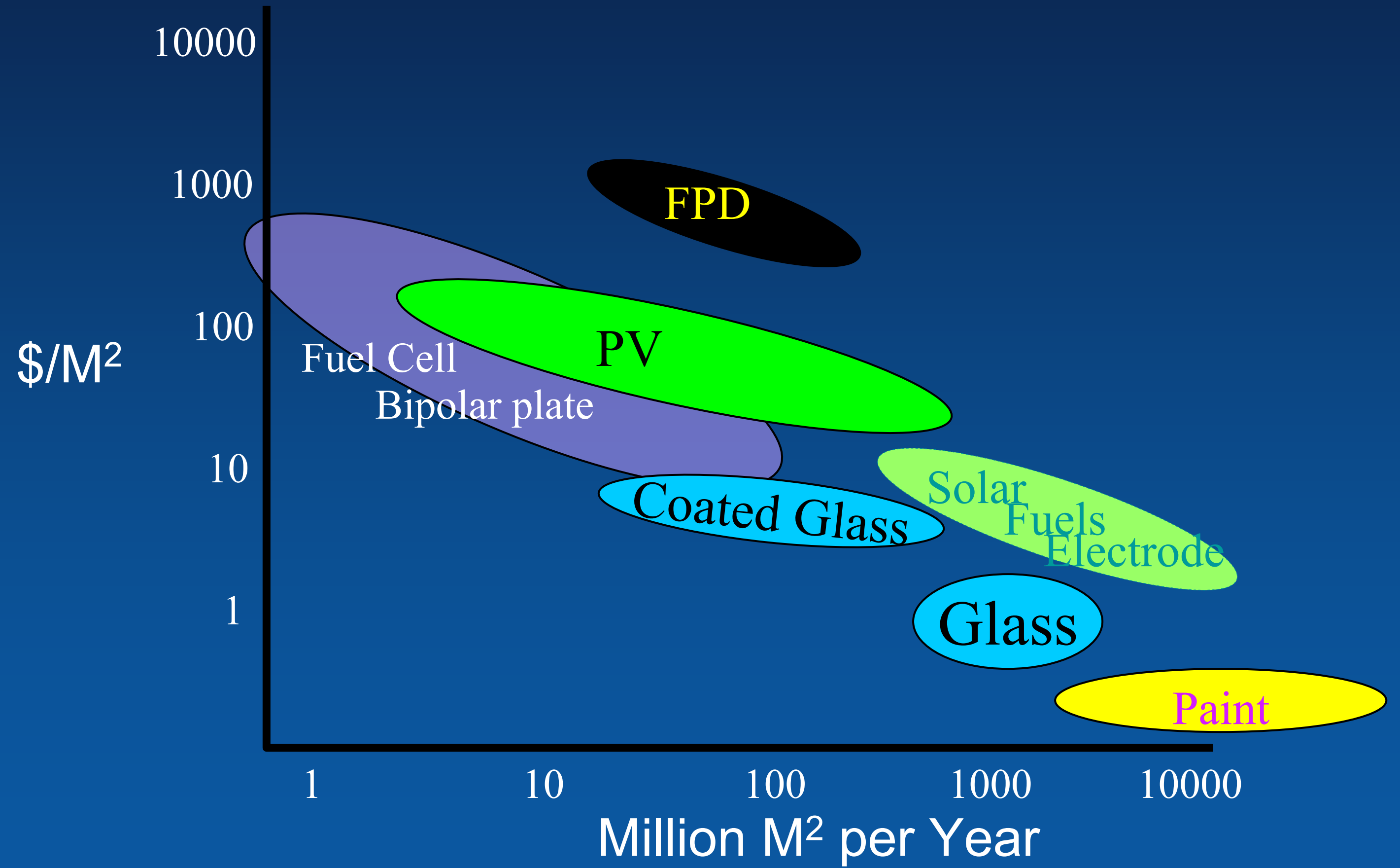
Energy Costs



www.undp.org/seed/eap/activities/wea

Low Cost Processes

Large-Area Optical and Electronic Materials



Solar Technology Opportunities

- Source of Carbon Free Power
- Solar energy is the only currently practical primary source in sufficient abundance to sustain growing energy demand for centuries to come.
- Massive change to energy infrastructure requires decades to implement, along with massive investment.